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# Ground Cloud Dispersion Measurements During The Titan IV Mission #K13 (20 December 1996) at Vandenberg Air Force Base

## Volume 1—Test Overview and Data Summary

10 October 1997

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Environmental Systems Directorate
Systems Engineering
Space Launch Operations

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Launch plume visible and infrared imagery were accomplished during the launch of Titan IV Mission #K13 at Vandenberg Air Force Base on 20 December 1996. These data will be used to improve the accuracy of the Rocket Exhaust Effluent Diffusion Model (REEDM). The imagery from three sites measured a cloud stabilization height of 828 m AGL compared to a REEDM-predicted stabilization height at 753 m AGL. This height was reached in 4 to 7 min compared to a REEDM prediction of 3.67 min. The imagery-derived cloud trajectory was 296° compared to the 332° trajectory predicted by REEDM. Measurements of aerial and ground-level concentrations of hydrogen chloride (HCl) were not taken during this launch.

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## Preface

The Air Force Space and Missile Systems Center's Launch Programs Office (SMC/CL) is sponsoring the Atmospheric Dispersion Model Validation Program (MVP). This program is collecting launch cloud dispersion data that will be used to determine the accuracy of atmospheric dispersion models, such as REEDM, in predicting toxic hazard corridors at the launch ranges. This report presents launch cloud dispersion and meteorological measurements performed during the #K13 Titan IV launch at Vandenberg Air Force Base on 20 December 1996.

An MVP Integrated Product Team (IPT) led by Capt. Brian Laine (SMC/CLNM) is directing the MVP effort. Dr. Bart Lundblad of The Aerospace Corporation's Environmental Systems Directorate (ESD) is the MVP technical manager. This report was prepared by Mr. Norm Keegan (ESD) and Dr. Lundblad from materials contributed by personnel participating in the #K13 launch cloud dispersion measurements.

Visible and infrared imagery measurements were made of the launch cloud by Dr. Robert Abernathy, Ms. Karen Foster, Mr. Gary Harper, Mr. Brian Kasper, Mr. Tom Knudtson, Mr. Mike Rocha, and Ms. Janet Webb of The Aerospace Corporation's Environmental Monitoring and Technology Department (EMTD). Mr. Jim Kephart of Aerospace's Western Range Directorate coordinated camera site selection and logistical support. Ms. Foster digitized the imagery data for analysis by Dr. Abernathy. The description of the cloud imagery results was prepared by Dr. Abernathy.

The meteorological data displayed in this report was provided by Mr. Steve Sambol of the VAFB Weather Squadron (30WS/DOS). The REEDM launch cloud dispersion prediction was provided by Dr. Abernathy based on input received from Mr. Darryl Dargitz of the VAFB Range Safety Office (30 SW/SEY) and Mr. Randy Nyman (ACTA, Inc.).

The #K13 mission was the ninth Titan IV launch for which usable launch cloud dispersion data was collected by MVP. The previous missions were #K7, #K23, #K19, #K21, #K15, #K16, #K22, and #K2.

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## Executive Summary

This report presents plume imagery documenting the development and dispersion of the Titan IV #K13 launch ground cloud at Vandenberg Air Force Base (VAFB). The launch occurred on 20 December 1996 at 1004 PST. The report also presents pertinent meteorological data taken from towers and rawinsonde balloons.

The imaging team successfully tracked the trajectory and time evolution of the vehicle's exhaust ground cloud for 11 min following launch using three visible-light camera systems. Meteorological data were collected to improve understanding of cloud dispersion and to use as input during model simulations and evaluations. Rawinsonde balloon data from shortly before launch and meteorological tower data from shortly before and after launch were collected and archived. These data and similar data on other Titan IV launches (past and future) will be used to determine the accuracy of atmospheric dispersion models such as the Rocket Exhaust Effluent Diffusion Model (REEDM) in predicting toxic hazard corridors (THCs) at the USAF Eastern and Western Ranges. These THCs assess the risk of exposing the public to HCl exhaust from solid rocket motors or hypergolic propellant vapors accidentally released during launch operations.

Reduction of imagery data from the first 11 min following launch yielded the stabilization height, rise time, ground track, and speed of the ground cloud. Comparison to REEDM 7.08 predictions show that the imagery-derived stabilization height (828 m) is 10% higher than predicted by REEDM (753 m) and that the imagery-derived time to stabilization (4–7 min) is 9–91% longer than the REEDM-predicted stabilization time (3.67 min). The imagery-derived ground track of the cloud (116°) is 34° more counter-clockwise than predicted by REEDM (150°) and the imagery-derived velocity of the cloud (2.6 m/s) is slower than predicted by REEDM after cloud stabilization (5.5 m/s).

# 1. Introduction

Launch vehicles that employ solid-propellant rocket motors release exhaust ground clouds containing large quantities of hydrogen chloride (HCl) into the launch areas at Cape Canaveral Air Station (CCAS) and Vandenberg Air Force Base (VAFB). Large quantities of hazardous liquid fuels and oxidizers could also be released as a result of propellant transfer accidents or launch vehicle failures. The Air Force uses atmospheric dispersion models to predict the downwind diffusion and concentration of toxic launch clouds. Collection of launch cloud data is required to test and validate the performance of these dispersion models.

The Air Force range safety organizations at Patrick Air Force Base (45 SW/SE) and VAFB (30 SW/SE) are responsible for assuring that launches occur only when meteorological conditions will not expose nearby public areas to hazardous levels of launch exhausts and propellant vapors. Predictions of toxic hazard corridors that extend into public areas can lead to costly launch delays. The use of non-validated models requires the use of conservative launch criteria. The development and validation of more accurate atmospheric dispersion models is expected to increase launch opportunities and significantly reduce launch costs. The Space and Missile Systems Center's Launch Programs Office (SMC/CL) established the Atmospheric Dispersion Model Validation Program (MVP) to collect launch cloud data and to use the data to test and validate current and future atmospheric dispersion models at the ranges.

The MVP effort involves the collection of data during Titan IV launches at CCAS and VAFB to characterize HCl launch cloud rise, growth, and stabilization, as well as launch cloud transport and diffusion. These data, along with data collected during tracer gas releases, will be used to determine the capability of the Rocket Exhaust Effluent Diffusion Model (REEDM) for predicting toxic hazard corridors at the ranges. REEDM is used at CCAS and VAFB to predict the locations of toxic hazard corridors in support of launch operations. It is applied to large heated sources of toxic air emissions such as nominal launches, catastrophic failure fireballs, and inadvertent ignitions of solid rocket motors. It uses launch vehicle and meteorological data to generate ground-level concentration isopleths of HCl, hydrazine fuels, nitrogen dioxide, and other toxic launch emissions. Launch holds may occur when REEDM toxic concentration predictions exceed adopted exposure standards. REEDM is a unique and complex model based on relatively simple modeling physics. It has a long development history with the Air Force and NASA, but has never been fully validated. Validation of REEDM has been identified as a range safety priority.

The MVP has been organized and is being directed by the MVP Integrated Product Team (IPT). SMC/CL is serving as the IPT leader, while The Aerospace Corporation's Environmental Systems Directorate serves as the IPT technical manager. The IPT consists of personnel with expertise in atmospheric dispersion modeling, meteorology, and atmospheric dispersion field studies. MVP participants include personnel from SMC, 30 SW, 45 SW, Armstrong Laboratory, The Aerospace Corporation, NASA, NOAA, and contractors. Key functions include program planning, field data collection, data review and compilation, range coordination, and model validation.

This report presents the results of measurements performed at VAFB during the Titan IV #K13 launch on 20 December 1996 at 1004 PST. Visible and infrared measurements were made on the ground cloud to monitor its growth, stabilization, and trajectory. The imagery results are presented in Section 2, and REEDM predictions of ground cloud stabilization heights and surface concentrations are presented in Appendix A. Measurements of meteorological data are tabulated in Appendix B.

The imagery data obtained show that the T-0.3h REEDM 7.08 calculation underestimates cloud stabilization height (828 m vs. 753 m predicted), underestimates cloud stabilization time (4–7 min vs. 3.67 min predicted), and overestimates cloud speed after stabilization (2.6 m/s vs. 5.5 m/s predicted). The imagery results presented in this, as well as other MVP reports, will allow the accuracy of REEDM and other launch range atmospheric dispersion models to be determined over the range of possible meteorological conditions.

# 2. Imagery of the Titan IV #K13 Ground Cloud

[The material in this section was contributed by R. N. Abernathy, K. L. Foster, B. P. Kasper and J. Y. Webb of the Environmental Monitoring and Technology Department of The Aerospace Corporation's Space and Environment Technology Center.]

## 2.1 Background

The Aerospace Corporation has been deploying visible and/or infrared imaging systems to Titan IV launches since the #K10 Launch on 07 February 1994. These deployments include Titan IV missions #K2, #K7, #K9, #K10, #K13, #K14, #K15, #K16, #K19, #K21, #K22, and #K23 as well as the first SRMU mission #K24 "B." Typically, two-dimensional cloud images are recorded at each of two to three imaging sites and are combined in a pairwise fashion to produce stereoscopic 3-D information about the exhaust cloud. When atmospheric conditions were favorable and two (or more) imagery sites were manned (i.e., #K2, #K7, #K13, #K15, #K16, #K19, #K21, #K22, #K23, and #K24), the analysis of these data yields the ground cloud's rise time, stabilization height, dimensions, ground track, and ground speed. These imagery-derived data and the resulting cloud characteristics are available to modelers as part of the model validation program (MVP).

For #K13, all three selected imagery sites yielded data useful for tracking the cloud. The analysis of the first 11 min of the imagery data yields the ground cloud's rise time, stabilization height, ground track, and speed. The raw visible imagery data were recorded by a VCR. A PC-based image-capture board allowed the digitization of selected images from the VCR tapes. Subsequently, all of the imagery data that were processed for this report were archived on magneto-optical disks as digital image files.

## 2.2 Introduction

On 20 December 1996, the Titan IV #K13 mission was successfully launched from VAFB SLC-4E at 10:04 PST (18:04 GMT). This section describes the exhaust cloud imagery data collected by three imagery sites during the 31 min immediately following the launch. It also briefly describes the data acquisition hardware and analysis software. Analysis of the first 11 min of this imagery yields the stabilization time, the stabilization height, the ground track, and the speed of the ground cloud without recourse to additional data sources. Rudimentary knowledge of the rawinsonde wind data is needed for more quantitative interpretation of the imagery data reported in this section. The pre-launch rawinsonde data are documented in Appendix B and referenced in this section. REEDM predictions are documented in Appendix A and referenced in this section.

## 2.3 Field Deployment

### 2.3.1 Planning

The Aerospace Corporation's participants are listed in various subteams below (members of the imaging teams for #K13 are indicated with asterisks and paired with the imagery sites they supported):

Technology Operations
Space and Environment Technology Center
Environmental Monitoring and Technology Department

| | | |
|---|---|---|
| G. N. Harper* | B. P. Kasper* | (Wall Beach) |
| J. T. Knudtson* | | (Tetra Tech) |
| K. L. Foster* | J. Y. Webb* | (Tetra Tech) |
| R. N. Abernathy* | M. A. Rocha* | (Steward4 RM1) |

Space Launch Operations
Systems Engineering Directorate
Environmental Systems
N. F. Dowling, Systems Director
H. L. Lundblad
Western Range
Systems Engineering Directorate
E. J. Tomei, Systems Director
J. F. Kephart

### 2.3.2 Equipment

The equipment at each site included all the hardware and software necessary to record and document the launch, to communicate between sites, and to supply backup power in case of a power outage. Since none of the sites had access to power, all Sites used gasoline-powered generators for the #K13 mission. The launch of #K13 marked the eighth opportunity to deploy the Titan IV-dedicated Visible and Infrared Imaging System (VIRIS) hardware.

The VIRIS consists of an array of four cloud tracking systems and was designed and fabricated at the request of Space Launch Operations, Systems Engineering Directorate, at The Aerospace Corporation. Three of the tracking systems include coaligned visible and infrared (IR) (8–12 μm) imagers, mounted on an azimuth- and elevation-encoding tripod, with an associated data acquisition and display console. The fourth tracking system does not include an infrared imager. The combination of visible and IR imagers permits cloud tracking in both daylight and darkness. The #K13 launch was a daylight launch, and only the visible imagery was used to track the cloud. The unique capabilities built into the VIRIS hardware include digital insertion of imager azimuth (Az), elevation (El), GPS-derived time, and GPS-derived location into the VCR recording of the imagery. The system electronics are integrated in a single package, which has been ruggedized for field use. Pre-wiring of this package makes deployment of these imagery systems straightforward, usually requiring less than 45 min for instrumentation at a site to become fully operational. For the Titan IV #K13 mission, the operators at all sites set the FOVs of the visible

imagers to their maximum values (i.e., equivalent to an 11 mm lens). Table 1 summarizes the FOVs of the imagery sites for the #K13 launch.

The imaging systems deployed for the Titan IV #K13 mission were capable of total autonomy. At VAFB, the VIRIS's built-in GPS receivers could not receive differential correction broadcasts. Therefore, we used a Trimble Navigation portable differential GPS receiver to document each imager's position to a 2-m precision in the horizontal plane. Typically, 35 m is the precision in the horizontal plane for the VIRIS's differentially corrected data (i.e., for Cape Canaveral Air Station). Gasoline-powered AC generators (Honda Ex1000) are insurance against loss of fixed power and were used as the sole source of power at all sites. Each unit was transported in a van or sports utility vehicle (SUV).

The tripod's Az/El angle encoder for each imagery site was calibrated using reference objects (e.g., SLC-4E) within the field of view of the imagers. Typically, the position of the reference object is derived from the Department of Defense Geodetic Coordinates Database (WGS 1984 datum). Since the imagery sites used for the #K13 mission were surveyed using 2-m resolution differential GPS service, the accuracy (3-m standard error) of the reference object's location is a more significant term in determining the calibration accuracy. Imagery pixelation and operator error in edge detection contribute as well to the error in defining the cloud boundary. Step-size in the tripod angle encoders is a third and the most significant source of error. Therefore, the accuracy of the VIRIS system is usually determined by the availability of optimal references for Az/El calibration or by the encoder step size. A 0.07° accuracy applies to the Az/El calibrations used for the #K13 analysis and is equivalent to the encoder step size. Table 2 documents the imagery site locations (based upon the 2-m precision GPS survey) and their angles to SLC-4E pad. According to the 5 May 1996 DOD Geodetic Coordinates Manual using WGS 1984 Datum, SLC-4E is located at 34.632035° N, 120.610631° W, and 158 m (519 ft) MSL.

Table 1. Field of View (FOV) for Imagery Sites During #K13 Mission

| Imagery Site | Imager Type (Visible or IR) | FOV(horizontal) (°) | FOV(vertical) (°) |
|---|---|---|---|
| Wall Beach | Visible CCD | 31.55 | 24.10 |
| Tetra Tech | Visible CCD | 31.87 | 24.48 |
| Steward4 RM1 | Visible CCD | 31.62 | 24.38 |

Table 2. Imagery Site Positions and Angles (Bearing CW of North) to SLC-4E Pad

| Imagery Site | Latitude (°) | Longitude (°) | Altitude (MSL) (m) | AZ(SLC-4E) (°) | EL(SLC-4E) (°) |
|---|---|---|---|---|---|
| Block Wall | 34.706202 | -120.600496 | 5 | 186.41 | 1.06 |
| Tetra Tech | 34.692873 | -120.537945 | 108 | 224.50 | 0.30 |
| Steward4 RM1 | 34.614744 | -120.545488 | 421 | 287.88 | -2.40 |

## 2.4 Processing of Imagery Data

The processing of the imagery data requires several transformations that are performed upon return to The Aerospace Corporation:

1. Digitizing frames of visible imagery from the VCR tapes.
2. Measuring the pixel locations of the reference sites within each image (i.e., FOV and angular calibration).
3. Measuring the pixel locations of exhaust cloud features in digitized images.
4. Converting pixel locations to azimuth and elevation readings.
5. Calculating cloud characteristics (i.e., position in Cartesian coordinates relative to the launch pad and MSL).

The processing requires the use of specialized hardware and software. Time, Az, and El are tabulated for each digitized image. Sets of digitized images exist for selected times following the launch. A setup file is created for each pair of images and contains all relevant information necessary to compute the cloud geometry from the imagery. The Aerospace program **PLMTRACK** is run to digitize the x, y, and z coordinates of cloud features.

**PLMTRACK** is a software program developed in the Environmental Monitoring and Technology Department (EMTD) of The Aerospace Corporation by Brian P. Kasper. It is designed to analyze pairs of cloud images synchronized in time. The operator selects the location of a particular cloud feature in the images from the two imagery sites by moving a screen pointer over the desired point in each image and clicking a mouse button. **PLMTRACK** then calculates the three-dimensional location of this point and writes the information to a data file.

Another implementation of **PLMTRACK** is the "box method," illustrated in Figure 1. The operator draws a rectangle about a cloud feature in the images from the two imagery sites by moving a screen pointer to the extreme corners of the rectangles and clicking a mouse button. **PLMTRACK** then calculates the closest approach for various rays as illustrated in Figure 1 and described below. The top of the cloud is defined by rays determining T1 and T2 (i.e., T1 × T2); the bottom is determined by rays defining B1 and B2 (i.e., B1 × B2); and the middle is defined by the geometric mean of top and bottom (i.e., M1 × M2). To define the "faces" of the polygon surrounding the cloud, the points of closest approach for ray M1 with L2 and R2 (the left and right tangents to the cloud from Imager 2) are defined (i.e., M1 × L2 and M1 × R2). A similar procedure is used to define the points of closest approach for M2 with L1 and R1, yielding M2 × R1 and M2 × L1. Thus, seven points are defined for the "cell" surrounding the cloud (a point in the center of each of the six faces, plus a middle point for the cell). Four additional points are calculated by **PLMTRACK** (L1 × L2, L1 × R2, R1 × L2, and R1 × R2), and they define the extreme vertices of a polygon projected onto the ground plane and surrounding the observable cloud. All eleven points are written to a comma-separated-variable (csv) file.

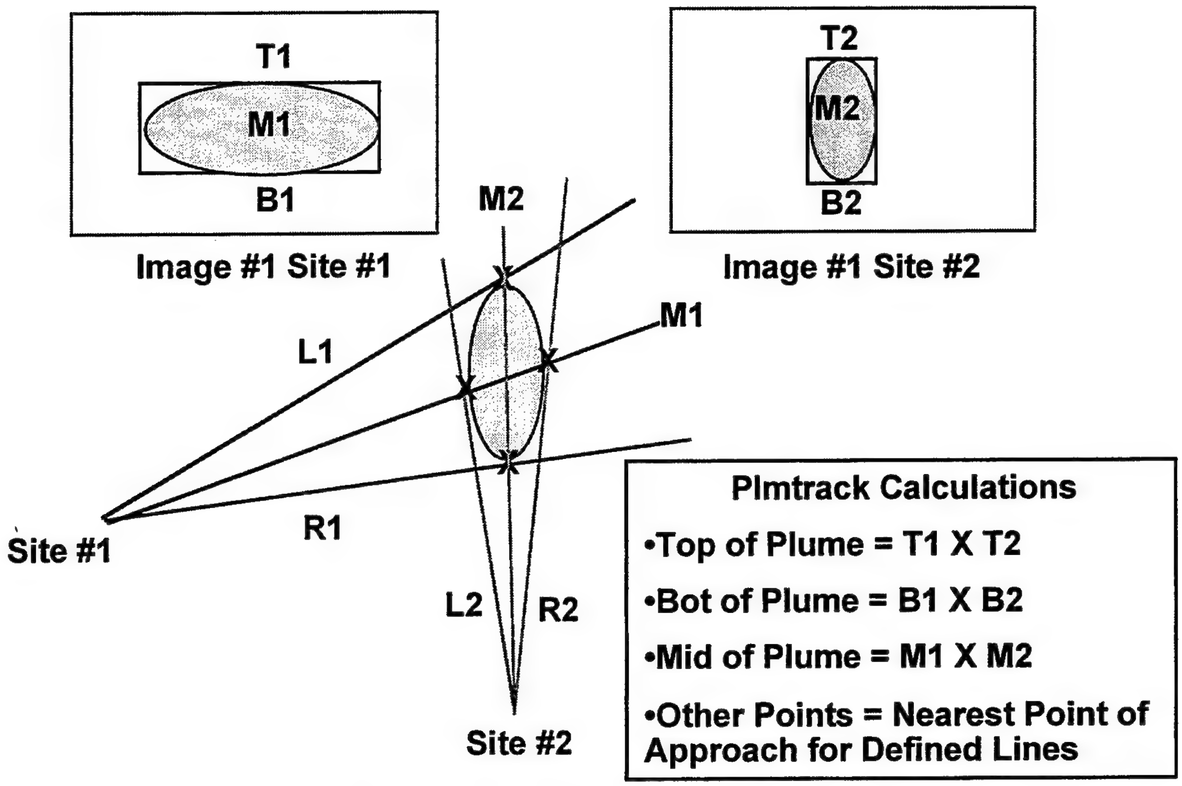


Figure 1. Implementation of the "box" method with two imagers.

When three (or more) imagers are viewing the cloud simultaneously (as accomplished for #K2, #K13, #K15, #K16, #K19, #K22, #K23, and #K24), a six-sided polygon method (documented in Figure 2 for the #K13 mission) can been employed as an initial step to determine cloud volume as a function of time. With three imagers, there is a triply redundant determination of the top, middle, and bottom of the cloud by **PLMTRACK**. The horizontal extent of the cloud is determined by defining the rays from each imager that are tangential to the widest part of the cloud as seen from that site. Projection of these extreme rays for each imager on the x-y ground plane forms a six-sided polygon (for three sites) that bounds all material in the ground cloud at all altitudes, as shown in Figure 2. When the polygon area is combined with the mean cloud height (i.e., the difference between the top and the bottom of the cloud), one can obtain an upper bound for cloud volume. This upper bound volume may *significantly* overestimate the volume of the cloud, as illustrated by Figure 2, by the relative areas of the polygon and of the cloud outline.

Examination of Figure 2 reveals almost ideal deployment of the three imagery sites. The sites viewed the cloud from the north, northeast, and east. This configuration provided excellent triangulation of the cloud's position and good estimates of its volume. As illustrated by the imagery included in this report, it is easier to image the cloud against the sky than against the terrain. Therefore, one prefers sites at or below the pad's altitude. The imagery site located to the east of the pad was slightly higher than the pad. In addition, a hill blocked its view of all but the top of the SLC-4E Mobile Service Tower (MST). Therefore, the eastern site could not observe the bottom of the cloud until it cleared the hilltop (i.e., approximately 1.5 min after launch). These

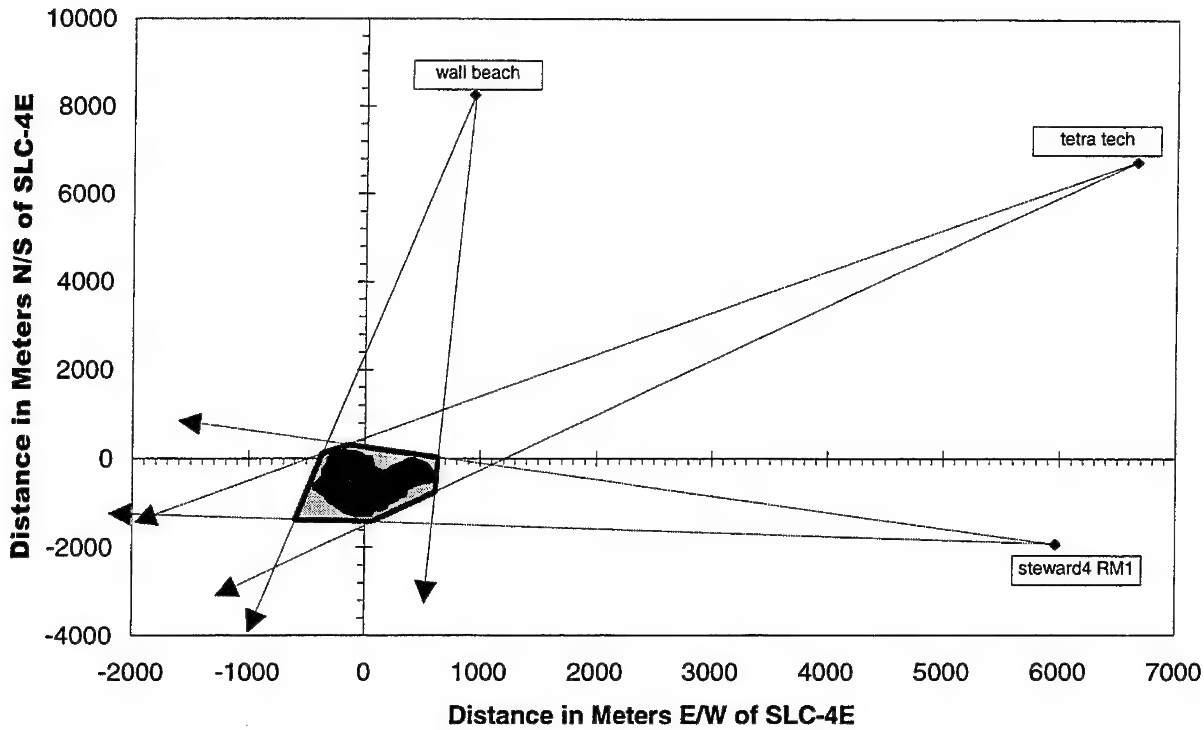


Figure 2. Implementation of the six-sided polygon method for three imagers. The imager positions and rays are actual #K13 data for imagery collected 4 min after launch. The cartoon of the cloud was synthesized for heuristic purposes to illustrate the potential for overestimation of the clouds size by the polygon method.

three sites were the best for viewing a launch from SLC-4E. We are not able to deploy south of the pad because of exclusion zones (chemistry and debris). The ocean is to the west of the pad.

## 2.5 Results and Discussion

### 2.5.1 Correlation of Ground Cloud Trajectory with Wind Direction

Figure 3 plots various wind and cloud bearings using the rawinsonde convention (defined fully in Subsection 2.5.5). Briefly, all cloud angles are reported as the angle (clockwise from north) from which the wind would blow to move the cloud along the predicted or measured bearing. The cloud trajectories are anchored to SLC-4E on the map. The heaviest arrow (i.e., thickest linewidth) is used to plot the 296° cloud direction derived from visible imagery using the **PLMTRACK** Box Method. Three additional cloud vectors are included to document the REEDM output that applies to the predicted exhaust cloud trajectory: (1) the 339° bearing of the cloud during rise; (2) the 332° bearing to maximum concentration at 753 m (i.e., REEDM's T-0.30h prediction for the stabilization height); and (3) the 322° average wind bearing for the second mixing layer (i.e., this dominates the vector of the stabilized cloud at later times). Since the #K13 imagery data extends to 11 min, well after stabilization, we will use the 322° REEDM pre-

diction for the cloud trajectory after stabilization when comparing trajectories. To the far left of the map in Figure 3, three wind vectors document the rawinsonde-derived wind directions associated with the bottom (53°), middle (336°), and top (318°) of the imagery-derived cloud heights. Although the rawinsonde originated from building 1764 (see Figure 3), the wind directions are anchored to the left of the map to avoid clutter. Figure 3 also documents the locations of the three imagery sites chosen by The Aerospace Corporation for the #K13 imagery.

It is evident from examination of Figure 3 and from the discussion in the preceding paragraph that REEDM predicts a cloud direction and speed (322° at 5.5 m/s after stabilization) that is rotated 26° more clockwise and is 208% faster than the imagery-derived cloud direction and speed (296° at 2.6 m/s). Likewise, it is evident from examination of Figure 3 that the imagery-derived southeasterly cloud direction and speed (296° at 2.6 m/s) is also significantly different from the T-0.30h rawinsonde-derived wind direction and speed (336° at 3.6 m/s) measured at a height equivalent to the middle of the stabilized ground cloud. The T-0.30h rawinsonde-derived data in Figure 3 are documented in Appendix B. The REEDM predictions in Figure 3 are documented in Appendix A.

We refer to "rawinsonde-derived" winds in this and subsequent discussions including Appendices A and B. Typically, the rawinsonde data collected above building 1764 are modified by Steve Sambol (or other VAFB weather personnel) using Doppler Acoustic Sounding System (DASS) data from near SLC-4E and meteorological tower data also collected near SLC-4E to better reflect winds experienced by the ground cloud near the pad. We used this T-0h reconstruction based upon the T-0.3h rawinsonde sounding as input to REEDM and for comparison to the imagery-derived cloud speed and direction. It is this rawinsonde-derived data that is included in Appendices A and B.

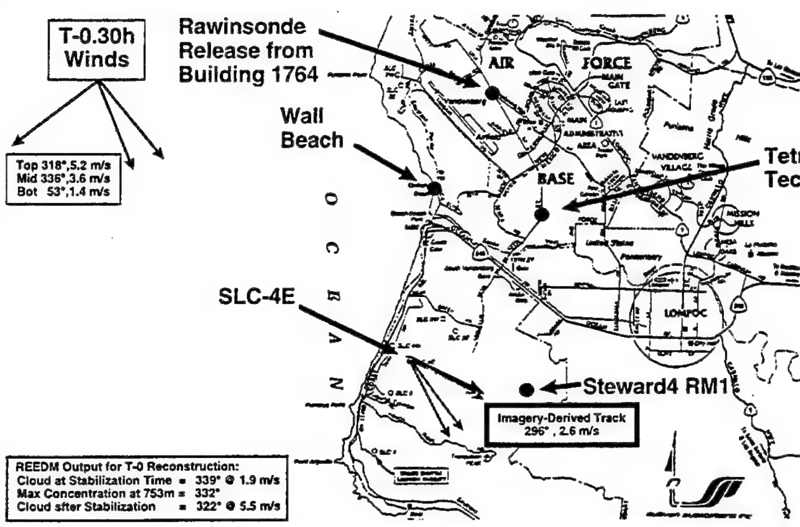


Figure 3. A map documenting the locations of the three imagery sites, the observed #K13 ground cloud's track (296°), the REEDM predictions for the #K13 exhaust cloud (339° during rise, 332° to maximum concentration at the stabilization height, and 322° for the cloud after stabilization), and the rawinsonde-derived wind directions for the top (318°), middle (336°), and bottom (53°) altitudes for the imaged cloud. The rawinsonde sounding was at 17:49 GMT (T-0.30h) from building 1764 site and was modified using DASS and Tower data to synthesize the T-0h reconstruction for REEDM runs.

## 2.5.2 Images of the Titan IV #K13 Exhaust Cloud

As discussed in the previous section, the imagery-derived cloud data is significantly different from the average T-0.30h rawinsonde-derived wind direction and speed (based upon a rawinsonde sounding from Building 1764 combined with DASS and Tower data near SLC-4E). The imagery documents a more easterly cloud track and slower movement than predicted by REEDM. Figures 4 through 8 are visible images of the Titan IV #K13 exhaust cloud as seen from the imagery sites at the specified times after launch. For clarity, boxes have been drawn about the "ground cloud." It is immediately obvious that the cloud is not spherically symmetric in any of these images.

Figure 4 documents visible imagery of the exhaust cloud and launch column at 15 s after launch as observed from all three sites. In Figure 4 (as in Figures 5 through 8), the four images can be labeled (CW from top left) as being from the following sites: Steward4 RM1, Tetra Tech, Wall Beach, and Tetra Tech (repeated for symmetry). In these images, the analyst identified the ground cloud as the wide portion of the cloud with the launch column extending upward from its middle. The analyst used the width of the ground cloud to differentiate it from the launch column during the first several minutes after launch. The visible imagery sees the cloud as illuminated by the sun (i.e., reflection and shadows depending upon the illumination angle). The

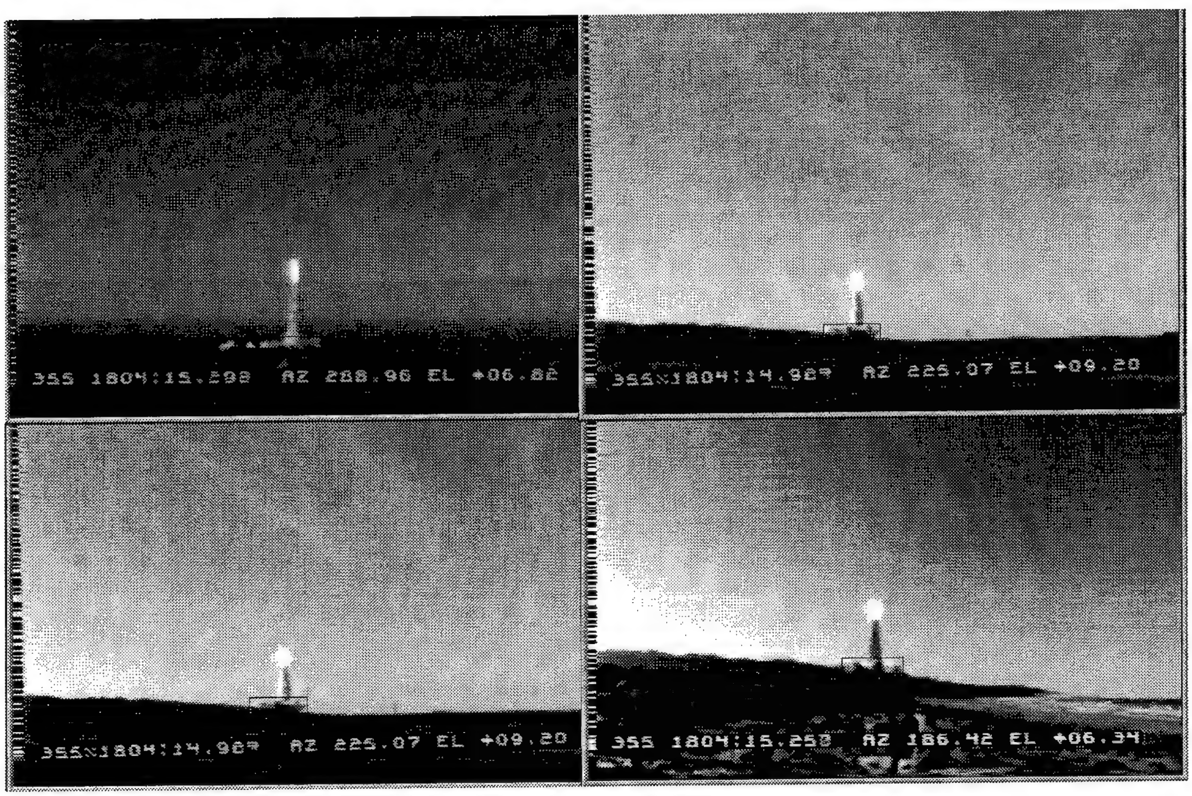


Figure 4. #K13 ground cloud, launch column, and Titan IV as observed at 00:15 (mm:ss) after launch. CW from top left the Images are from the following sites: Steward4 RM1, Tetra Tech, Wall Beach, and Tetra Tech (repeated for symmetry).

background for the visible imagery is dominated by scatter from the clouds as well as from aerosols in the lower atmosphere.

Figures 5, 6, 7, and 8 document the ground cloud at 1, 3, 7, and 11 min after launch as observed from all three sites. As in Figure 4, the four images in each figure can be labeled (CW from top left) as being from the following sites: Steward4 RM1, Tetra Tech, Wall Beach, and Tetra Tech (repeated for symmetry). It is apparent in these images that the signal-to-noise ratio changes with solar illumination angle, with distance from the cloud, and with time. As illustrated in Figures 2 and 3, the Steward4 RM1 site is closer to the pad than either the Tetra Tech or Wall Beach sites. Likewise, Figure 3 reveals that the cloud moves toward Steward4 RM1 site with time. The top and bottom of the "ground cloud" are defined by the analyst after careful review of previous and subsequent imagery from all imagery sites. The analyst draws his "box" about the mass of the cloud that contributes to the stabilized ground cloud.

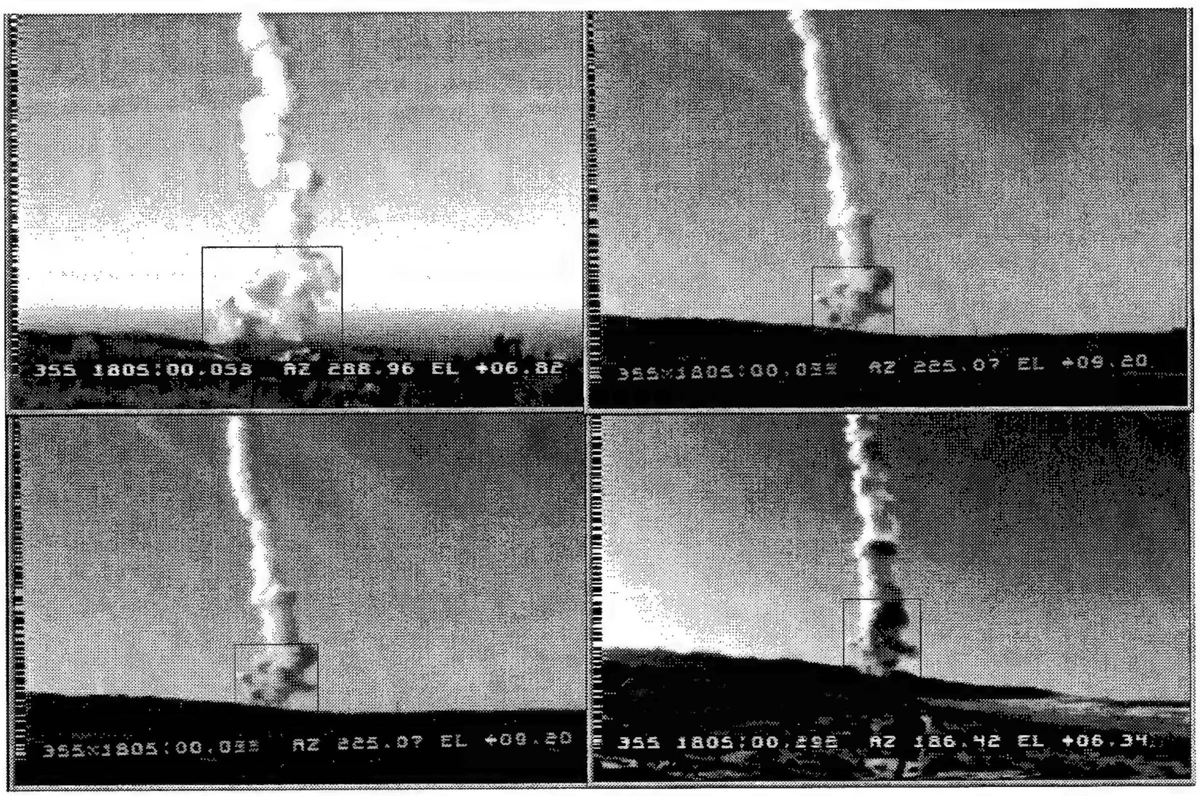

Figure 5. #K13 ground cloud with attached launch column as observed at 01:00 (mm:ss) after launch. CW from top left the Images are from the following sites: Steward4 RM1, Tetra Tech, Wall Beach, and Tetra Tech (repeated for symmetry).

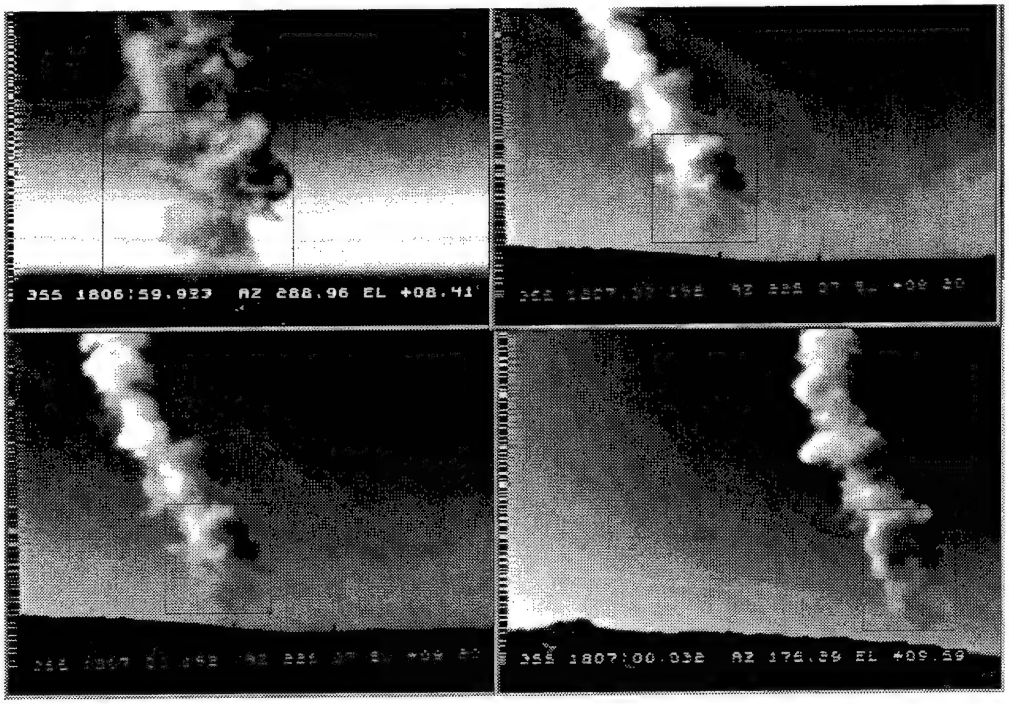


Figure 6. #K13 ground cloud with attached launch column as observed at 03:00 (mm:ss) after launch. CW from top left the images are from the following sites: Steward4 RM1, Tetra Tech, Wall Beach, and Tetra Tech (repeated for symmetry).

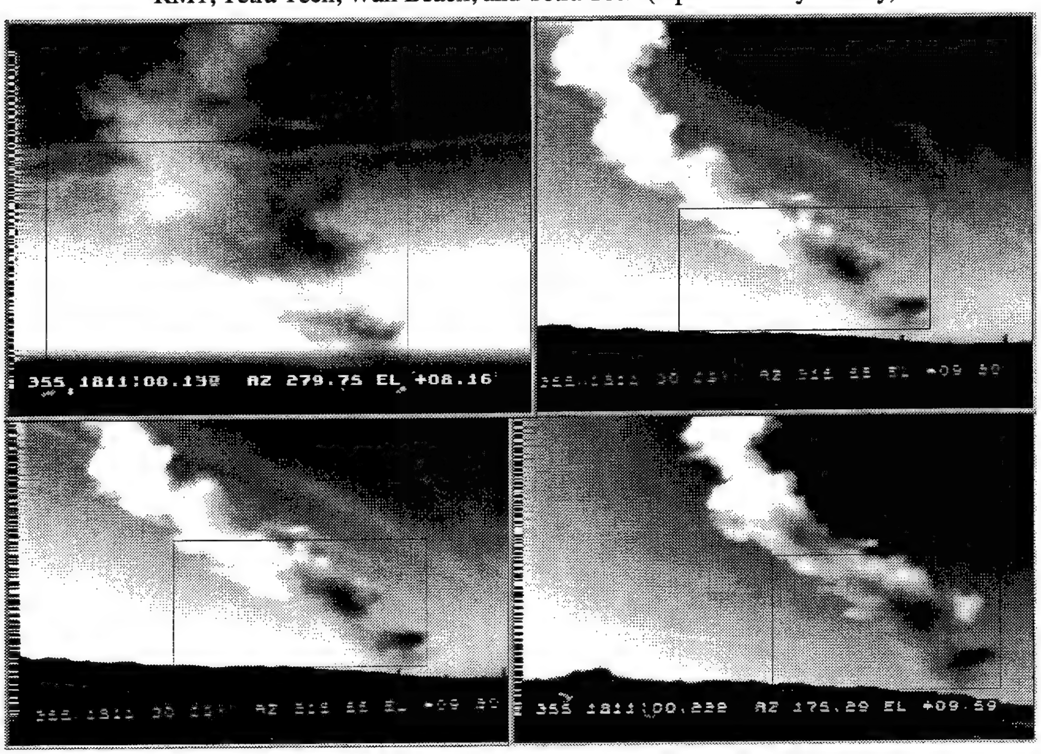


Figure 7. #K13 ground cloud with attached launch column as observed at 07:00 (mm:ss) after launch. CW from top left the images are from the following sites: Steward4 RM1, Tetra Tech, Wall Beach, and Tetra Tech (repeated for symmetry).

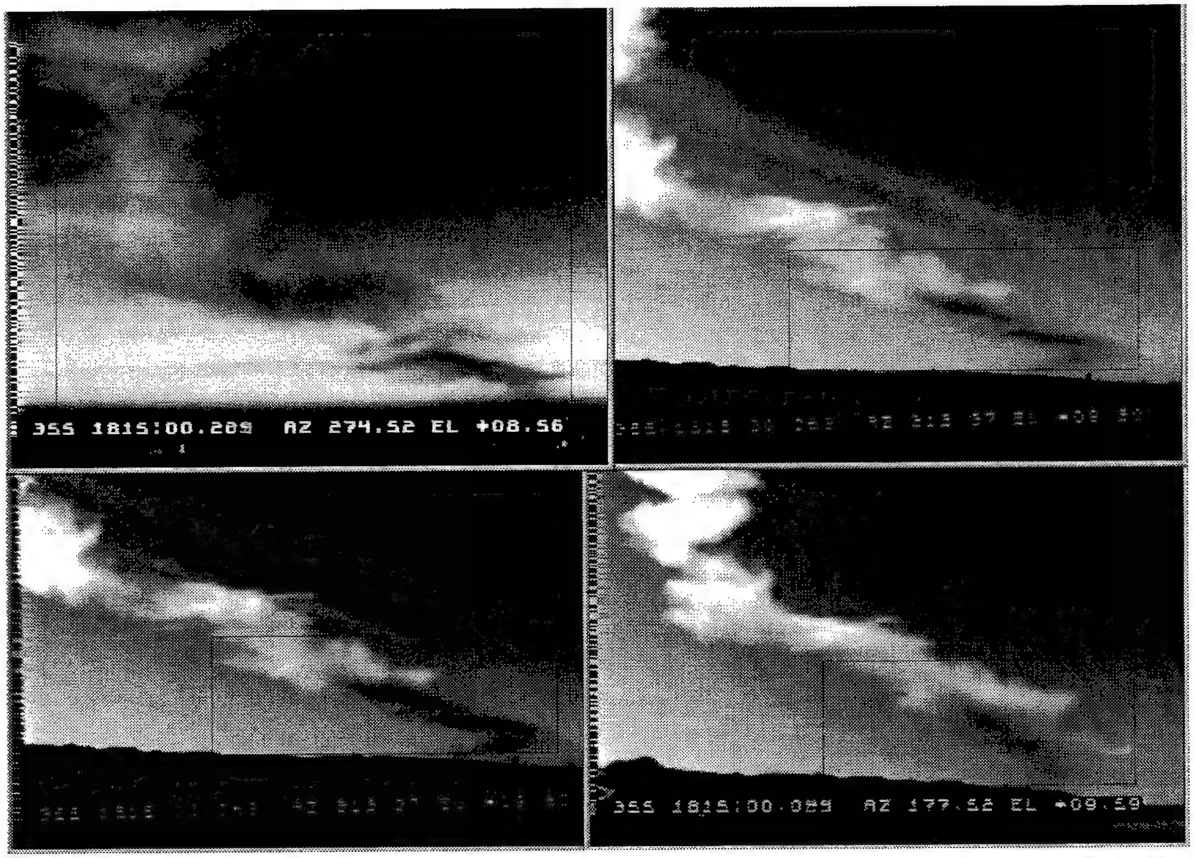


Figure 8. #K13 ground cloud with attached launch column as observed at 11:00 (mm:ss) after launch. CW from top left the images are from the following sites: Steward4 RM1, Tetra Tech, Wall Beach, and Tetra Tech (repeated for symmetry).

### 2.5.3 Cloud Rise Times and Stabilization Heights

The plots presented in Figures 9–11 show the time-dependent altitude (meters above SLC-4E = m AS4E) of the "bottom," the "middle," and the "top" of the ground cloud as derived from the quantitative imagery from the three camera sites. The "a" plots label the data according to pairs of images as follows:

| | |
|---|---|
| stte | visible imagery from steward4 and visible from tetra tech site |
| stwb | visible imagery from steward4 and visible from wall beach site |
| tewb | visible imagery from tetra tech and visible from wall beach site |

The labels on the "a" plots allow one to look for trends associated with certain combinations of imagery sites. Review of the "a" plots reveals that no single combination of sites produces systematically different results when compared to the other data over the entire monitoring time. Certainly the "a" plots support the treatment of the imagery data as one set as done in the "b" plots. The "b" plots include a polynomial fit to the combined data and horizontal lines illustrating the stabilization height as well as the $\pm 3\sigma$ error levels.

Since SLC-4E is at 158 m MSL and on the side of a hill, the bottom of the exhaust cloud initially has negative altitude due to its ejection downward from the rocket and along the slope of the hill near the pad. Similar values of "negative" altitude (relative to the pad) are not possible at Cape Canaveral since both SLC-40 and SLC-41 are at 7 m MSL and the terrain is flat.

It is evident from review of Figures 9–11 that the shapes of the cloud rise curves for the top, middle, and bottom of the ground cloud are dramatically different. The top of the cloud reaches its stabilization height within 4–7 min and slowly declines at later times. The bottom of the cloud reaches its stabilization height within 2.75–5.00 min and remains almost constant at later times. The middle of the cloud is calculated from the top and bottom. The cloud's characteristic rise times and stabilization heights are compared to REEDM predictions in the next section.

### 2.5.4. Comparison of REEDM Prediction to Imagery Data: Rise Rate and Height

In Figure 12, the imagery-derived heights for the cloud's top, middle, and bottom are plotted with the T-0.30h REEDM prediction of the height for the cloud's middle against time. It can be seen that the measured stabilization height of the cloud's center (828 ±12 m above SLC-4E) is 10% higher than the value predicted by REEDM (753 m in Appendix A) using pre-launch rawinsonde-derived data (Appendix B). The amount of time required to reach the stabilization height (approximately 4–7 minutes from the imagery) is 9 to 91% longer than the 3.67 min predicted by REEDM. This is evident from comparison of the shapes of the "middle" curves in Figure 12.

The variances ($R^2$) of the polynomial fits to the data (i.e., Figures 9–11) indicate that the fits are reasonably good. A polynomial fit was used in those figures as a convenient method to permit the representation of cloud overshoot and subsequent damped oscillation around the stabilization height. To be consistent with REEDM, stabilization time and height refer to the first maximum in these fits. REEDM predicts that the cloud goes through damped oscillatory motion with a period of $2\pi/S^{1/2}$, where S is the static stability parameter [Ref. 1, Eq. (7)].[1] Sensitivity of REEDM predictions to input parameters has been examined by Womack.[2] Careful imaging of launch ground clouds under a variety of meteorological conditions is a vital element in REEDM evaluation.

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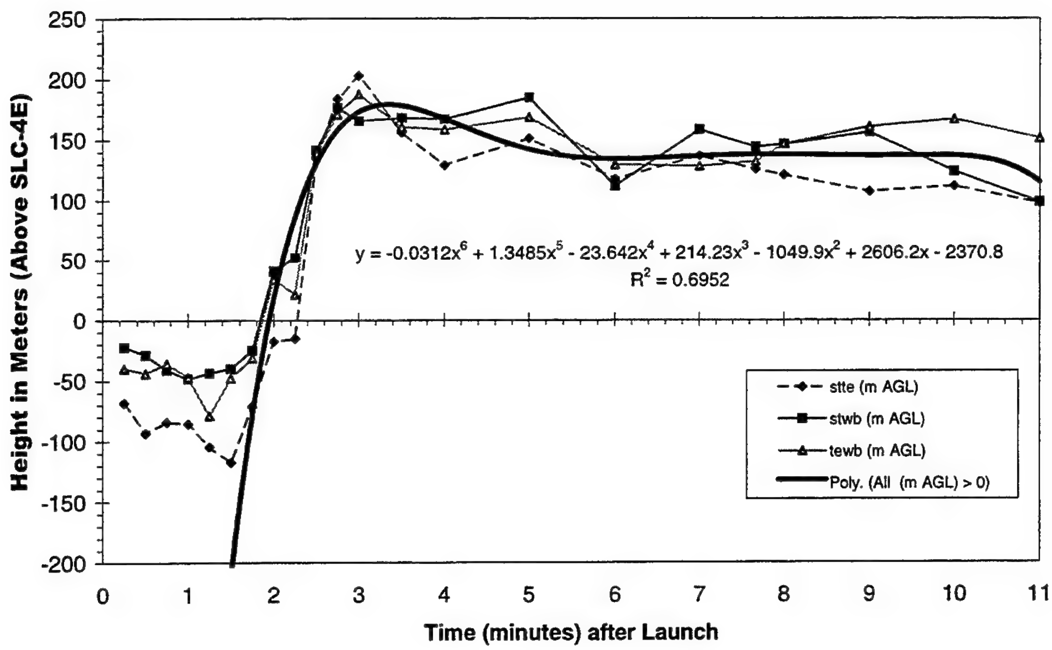
1 J. R. Bjorklund, User's Manual for the REEDM Version 7 (Rocket Exhaust Effluent Diffusion Model) Computer Program, Vol. I, TR-90-157-01, AF Systems Command, Patrick AFB, FL (April 1990).

2 J. M. Womack, *Rocket Exhaust Effluent Diffusion Model Sensitivity Study*, TOR-95(5448)-3, The Aerospace Corporation, El Segundo, CA (May 1995).



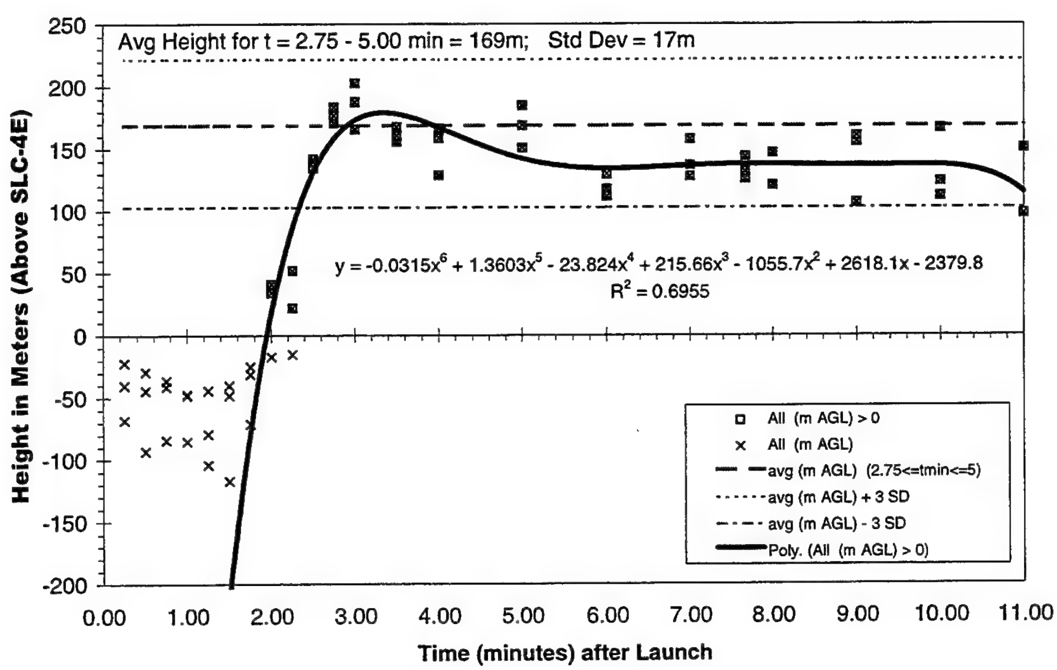
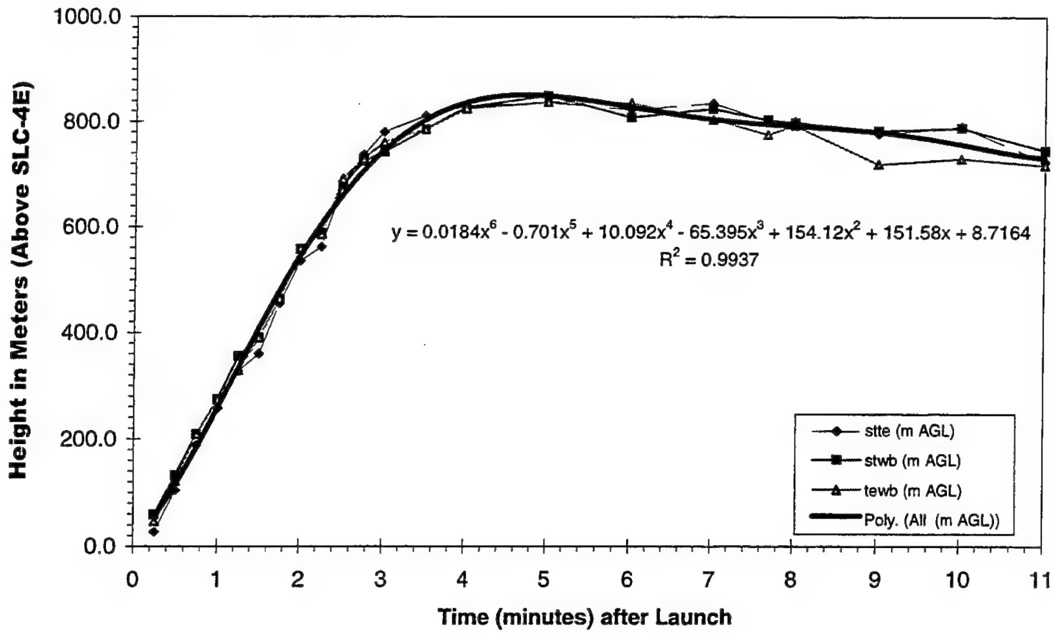




Figure 9. Cloud rise plot—bottom of #K13 ground cloud. (a) Cloud rise plot for the bottom of the #K13 cloud with data labeled by imagery pairs. (b) The values of height (m) vs t (min) are displayed with the sixth-order polynomial fits to all data and lines documenting the 3σ error bands, as well as the stabilization height (169 m [554 ft] above SLC-4E). The variance ($R^2$) of 0.6955 indicates the quality of the fit.



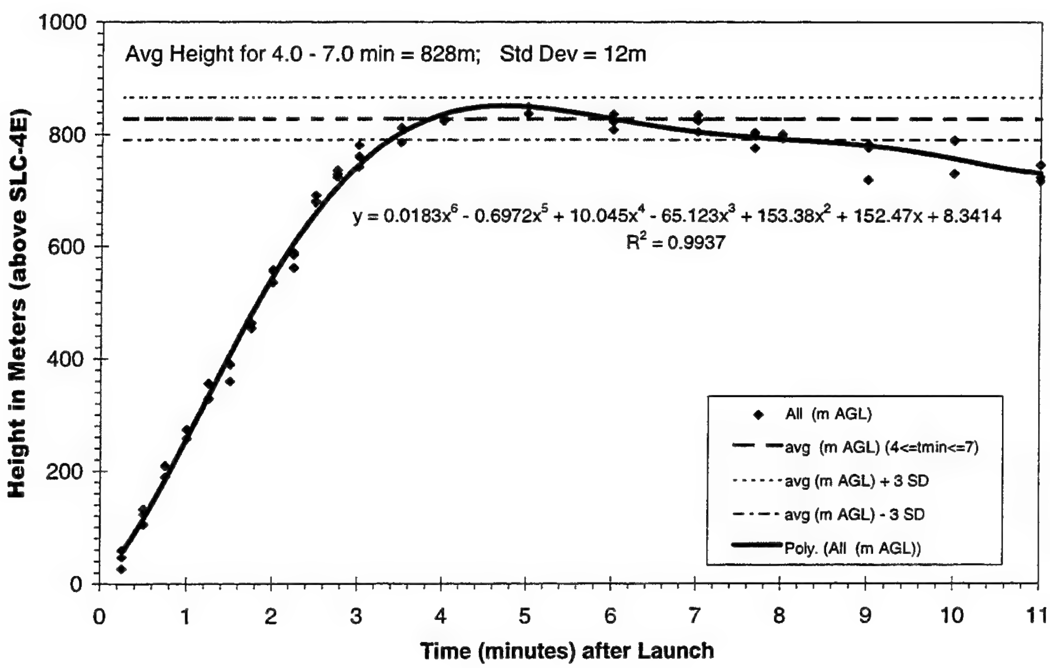
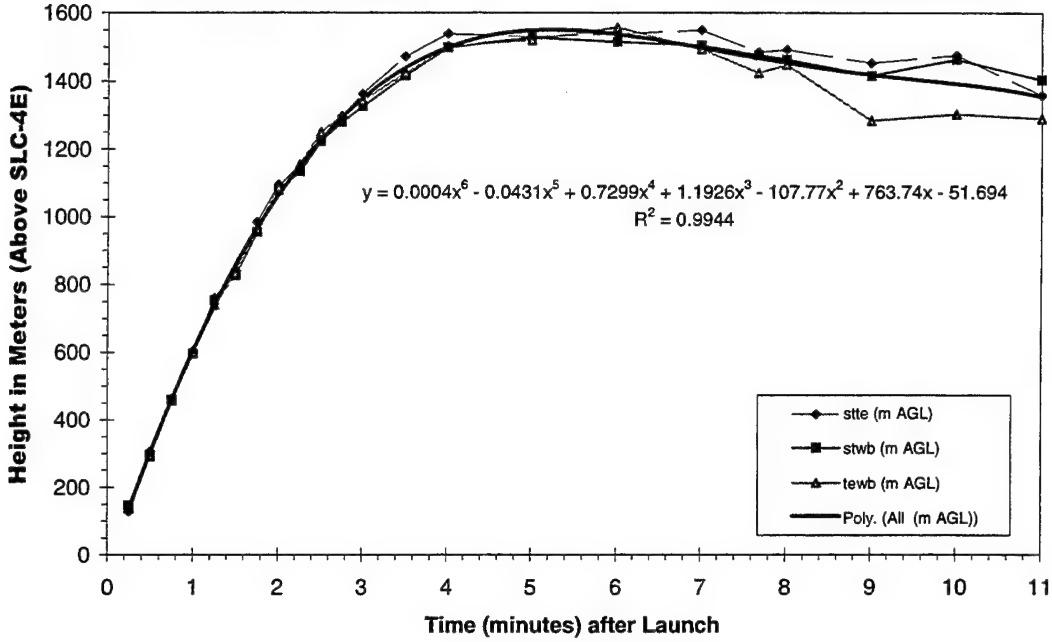




Figure 10. Cloud rise plot—middle of #K13 ground cloud. (a) Cloud rise plot for the middle of the #K13 cloud with data labeled by imagery pairs. (b) The values of height (m) vs t (min) are displayed with the sixth-order polynomial fits to all data and lines documenting the $3\sigma$ error bands as well as the stabilization height (828 m [2717 ft] above SLC-4E). The variance ($R^2$) of 0.9937 indicates the quality of the fit.



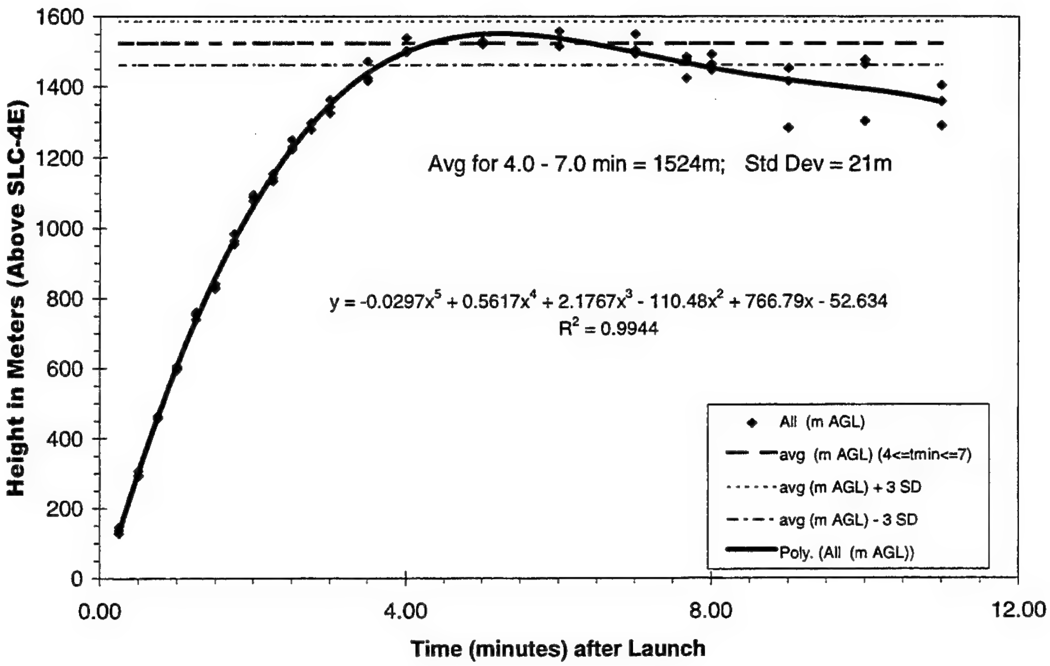




Figure 11. Cloud rise plot—top of #K13 ground cloud. (a) Cloud rise plot for the top of the #K13 cloud with data labeled by imagery pairs. (b) The values of height (m) vs t (min) are displayed with the fifth-order polynomial fits to all data and lines documenting the 3σ error bands as well as the stabilization height (1524 m [5000 ft] above SLC-4E). The variance ($R^2$) of 0.9944 indicates the quality of the fit.

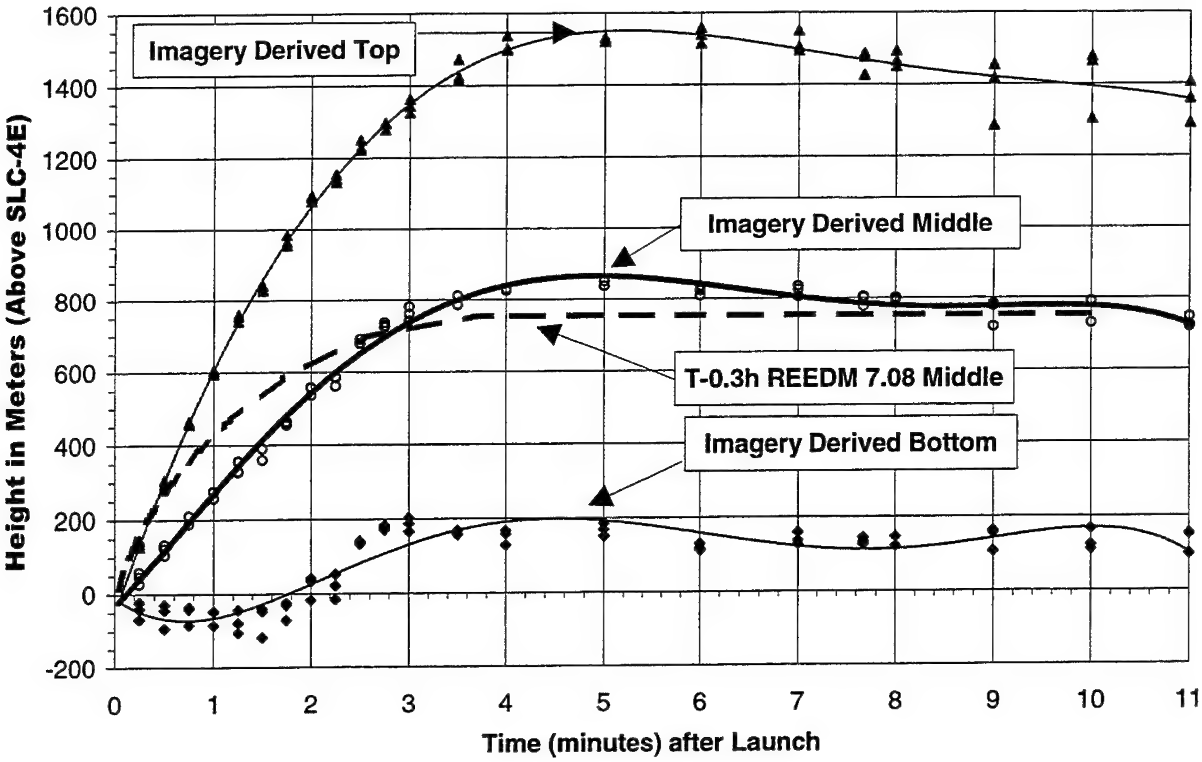



Figure 12. The imagery-derived heights for the top, middle, and bottom of the ground cloud (Figures 9–11) are plotted as H(t) vs t. The T-0.30h REEDM predictions for the cloud's middle (753 m after stabilization) are presented for comparison to the middle curve derived from the imagery (828 m to first maximum), which is 10% higher than the REEDM prediction.

### 2.5.5 Comparison of REEDM Prediction to Imagery Data: Trajectory and Speed

Figures 13, 14, and 15 present data for the ground track and for the displacement of the cloud from the launch pad as determined by imagery. The "box" method of analysis for the imagery data does not yield independent values of the cloud track for the top, middle, and bottom of the cloud. We have chosen to present data for the middle of the cloud as defined by **PLMTRACK**.

To be precise, the ground track in Figure 13 represents the ground plane projection of the trajectory of the middle of the cloud as a function of time. An "average" ground track is computed as a linear fit to the position data using the following formula:

$$Y = mX + b, \tag{1}$$

where Y is the distance in meters along the north-south axis, m is the slope of the fit, X is the distance in meters along the east-west axis, and b is the intercept for the fit. We normally permit the intercept (b) to be nonzero since the cloud origin may differ from the location of the launch

complex due to low-altitude winds and exhaust duct geometry. That displacement can also be modeled within the REEDM code.

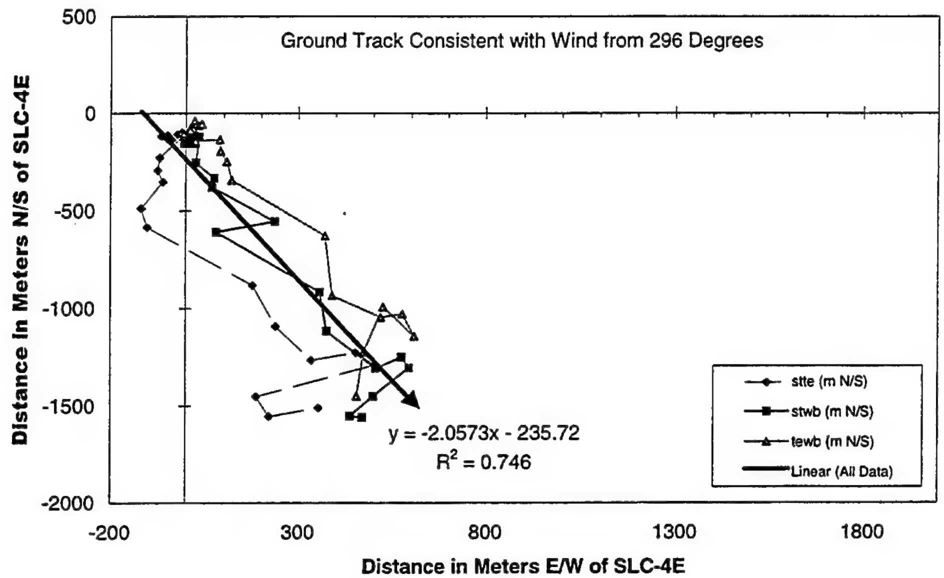



Figure 13. Ground track for the middle of the #K13 launch cloud. The cloud followed a southeasterly path as illustrated by the fitting all of the data to a line using linear regression. This 296° bearing is more easterly than the vectors reported by REEDM: (1) the 339° trajectory during rise, (2) the 332° bearing to maximum concentration at the 753 m (the predicted stabilization height), and (3) the 322° wind for the second mixing layer (affecting the cloud at later times). The rawinsonde-derived winds at the top (318°), middle (336°) and bottom (53°) of the imaged cloud document significant wind shear with altitude above building 1764.

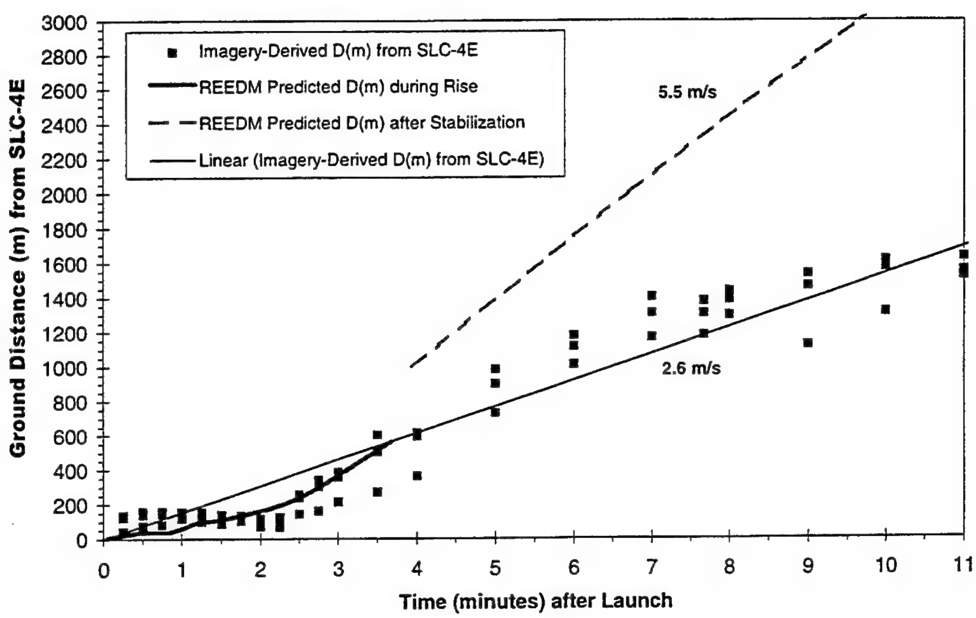



Figure 14. Imagery-derived ground distance versus time for the #K13 ground cloud compared to REEDM predictions for the rising and stabilized cloud.

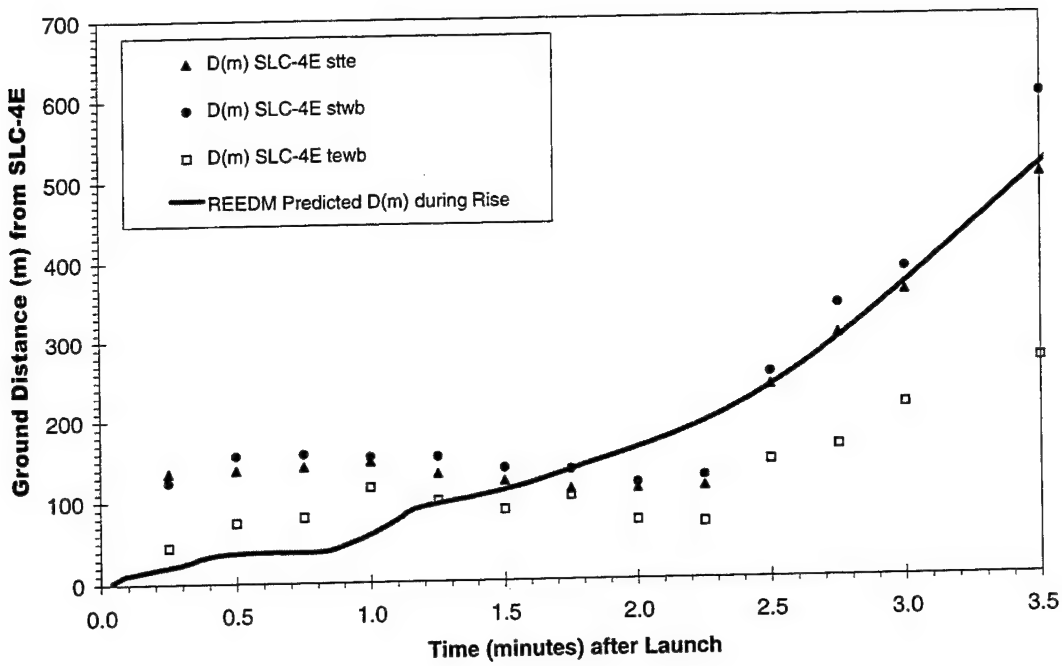



Figure 15. REEDM-predicted and imagery-derived ground distance versus time during the rise of the #K13 ground cloud.

In this report, the angles will conform to the convention of rawinsonde wind vectors (the angle (clockwise from north) from which the wind originates based on imaged cloud trajectory). Thus, the angles are related by

$$\vartheta = 180 + \Phi \tag{2}$$

where $\vartheta$ is the equivalent rawinsonde wind angle, and $\Phi$ is the measured polar angle of the cloud relative to SLC-4E and clockwise of true north. For example, when the cloud is due east of SLC-4E, $\Phi$ is 90° and $\vartheta$ is 270°. The slope (m) of the fitted line is determined by the angle $\theta$, where $\theta = \tan^{-1}$ m, and therefore $\Phi = 90° - \theta$.

Figure 14 presents the ground distance of the cloud from the launch pad as derived from analysis of pairs of imagery for 11 min after launch. The distance from SLC-4E increases with time. A linear fit to this trend provides the average velocity of the ground cloud (2.6 m/s cloud velocity away from SLC-4E). The high value for the variance for this linear fit (i.e., $R^2 = 0.9243$) illustrates the quality of this fit. However, there is an apparent shift in wind speed with time (i.e., with altitude). Figure 14 also presents REEDM (T-0.30h) predictions for the cloud during rise (first 3.5 min) and after stabilization (after 3.67 min). REEDM predicts an average cloud speed of 1.9 m/s during rise and a constant 5.5 m/s after stabilization. It is apparent in Figure 14 that REEDM's cloud rise prediction is in better agreement with the imagery-derived data than

REEDM's stabilized cloud prediction. For comparison, the T-0.30h rawinsonde-derived (Appendix B) wind speeds ranged from 1.4 m/s near the bottom, 3.6 m/s near the middle, and 5.2 m/s near the top of the cloud. The rawinsonde was launched at T-0.30h from building 1764 area (i.e., north-northeast of the pad). As mentioned previously, the rawinsonde-derived winds use the rawinsonde winds at high altitude but synthesize winds for low altitudes using DASS and Tower data collected closer to SLC-4E. In spite of these corrections, there may be offsets both in time and distance between the rawinsonde-derived winds and the winds experienced by the rising cloud.

Figure 15 presents a subset of the imagery-derived ground distance data presented in Figure 14 (i.e., only the first 3.5 min). In Figure 15, the imagery-derived data are labeled according to the imagery pairs. Apparently, the Steward4 site paired with either of the other sites yields distinctively different results those of Tetra Tech paired with Wall Beach. This is qualitatively consistent with better trigonometry using cameras with almost orthogonal viewing angles. Figure 15 reveals excellent qualitative agreement between REEDM prediction and imagery-derived cloud movement during cloud rise. This similarity between cloud behavior and REEDM prediction suggests that the cloud experienced wind shears very similar to those in the rawinsonde-derived input to REEDM.

### 2.5.6 Comparison of REEDM Prediction to Imagery Data: Summary Table

Table 3 summarizes the imagery-derived, rawinsonde-derived (T-0.30h), and REEDM-predicted cloud characteristics for the #K13 mission. As mentioned previously, the rawinsonde-derived winds and the REEDM prediction use a T-0h reconstruction based upon the T-0.30h rawinsonde sounding from building 1764, T-0h DASS profile above SLC-4E, and Tower 300 data. Several conclusions are derived from review of the contents of this table:

Table 3. Summary for #K13 Launch Cloud Data Derived from Visible imagery, T-0.30h Rawinsonde Sounding Data, & T-0.30h REEDM Prediction.

| Attribute | Feature | Imagery (Vis only) | Rawinsonde (T-0.3h) | REEDM 7.08 (T-0.3h) |
|---|---|---|---|---|
| Height (m) above SLC-4E | Top | 1524 | 1725 | 1362 |
| (SLC-4E = 158 m MSL) | Middle | 828 | 866 | 753 |
| | Bottom | 169 | 175 | 250 |
| Time (min) after launch | Top | 4.00–7.00 | #N/A | #N/A |
| | Middle | 4.00–7.00 | #N/A | 3.67 |
| | Bottom | 2.75–5.00 | #N/A | #N/A |
| Bearing (°) (rawinsonde) | Top | #N/A | 318° | #N/A |
| | Middle | 296° | 336° | 322° |
| | Bottom | #N/A | 53° | #N/A |
| Speed (m/s) away from | Top | #N/A | 5.2 | #N/A |
| SLC-4E | Middle | 2.6 | 3.6 | 5.5 |
| | Bottom | #N/A | 1.4 | #N/A |

(1) the imagery-derived direction and speed of the cloud are significantly different than the rawinsonde-derived average wind at the cloud's height;

(2) the imagery-derived stabilization height (828 m) is 10% higher than predicted by REEDM (753 m);

(3) the imagery-derived stabilization time (4-7 min) is 9% to 91% longer than predicted by REEDM (3.67 min);

(4) the imagery-derived average speed (2.6 m/s) of the ground cloud lies between REEDM's prediction of 1.9 m/s during rise and of 5.5 m/s after stabilization; and

(5) the imagery-derived cloud track (296°) is 26° less clockwise than predicted by REEDM (322°).

## 2.6 Summary and Conclusions

The Titan IV #K13 mission was launched successfully from the Eastern Range (SLC-4E) at 10:04 PST (18:04 GMT) on 20 December 1996. Personnel from The Aerospace Corporation deployed three visible imagery systems to monitor this daylight launch and to track the time evolution and the ground trajectory of the solid rocket motor exhaust cloud. The three imagery sites were located to the north, northeast, and east-southeast relative to launch complex SLC-4E. Imagery data were recorded for 31 min, and the cloud was tracked for 11 min. When combined with the Az/El readings and with the IRIG-B time data, the imagery was used to quantify movement, rise, and speed of the cloud for 11 min after the launch. The launch of #K13 marked the eighth deployment of the VIRIS imaging platforms to a Titan IV launch and the third VIRIS deployment for VAFB launch.

The definition of exhaust cloud geometric features was complicated by multiple contributions to the complex shape of the evolving cloud (i.e., rise of the hot ground cloud and shearing of the high-altitude launch column). The analyst included portions of the exhaust cloud based upon the review of all imagery.

Analysis of the imagery data presented in this report has focused on determining parameters that are directly comparable to REEDM predictions. The most accurately determined quantities by imagery are the cloud rise time, its stabilization height, cloud speed, and ground track. Using the combined T-0.30h rawinsonde data, the T = 0h DASS data, and the meteorological tower data, REEDM predicted a stabilization height of 753 m above ground level and a stabilization time of 3.67 min. The imagery-derived values were 828 m above SLC-4E and 4–7 min. The imagery-derived cloud trajectory was 296°, and the cloud's ground speed was 2.6 m/s away from SLC-4E. This compares to 322° and 5.5 m/s predicted by REEDM (using the T-0.30h rawinsonde data) for the stabilized ground cloud. Therefore, the imaged cloud stabilized at a height that was 10% higher than predicted by REEDM (T-0.30h), traveled at a speed 53% of that predicted by REEDM (T-0.30h), and headed in a direction 26° less clockwise than predicted by REEDM (T-0.30h).

# Appendix A—REEDM 7.08 Predictions for #K13 Mission (T-0h Revised)

Steve Sambol of the 30th weather squadron recommended some slight modifications to the T-0 weather reconstruction due to light winds measured on the DASS. This "New" input for REEDM resulted in a stabilization height of 753.4 m versus 754.1 m for the "Original" unmodified input, which was received from Mr. Randy Nyman (ACTA, Inc.)

This appendix includes REEDM Version 7.08 predictions using this "New" input named W6777RIN.NEW (Revised REEDM input weather file for T-0). The REEDM predictions apply to the predicted stabilization height of 753.4 m (AGL). The REEDM output were generated by R. N. Abernathy at The Aerospace Corporation.

Figures 1 through 3 document the meteorological output, HCl concentration profile, and HCl concentration isopleth plots generated by REEDM 7.08. Immediately following the plots is the detailed REEDM output text for the stabilized cloud height and normal launch. Page 1 of the output text is not included in this report since it provides typical error messages generated on REEDM runs. All heights are relative to ground level (AGL) unless otherwise stated in column headings.

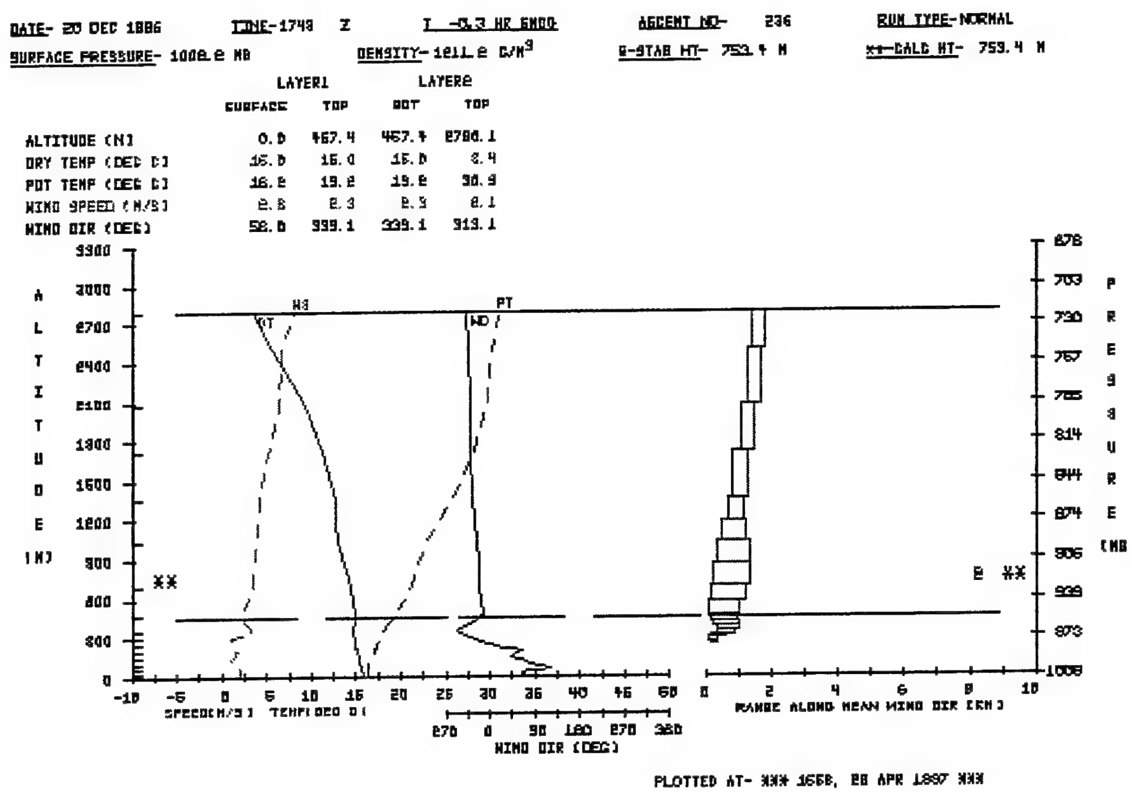


Figure 1. REEDM 7.08 meteorological prediction based upon T-0h input.

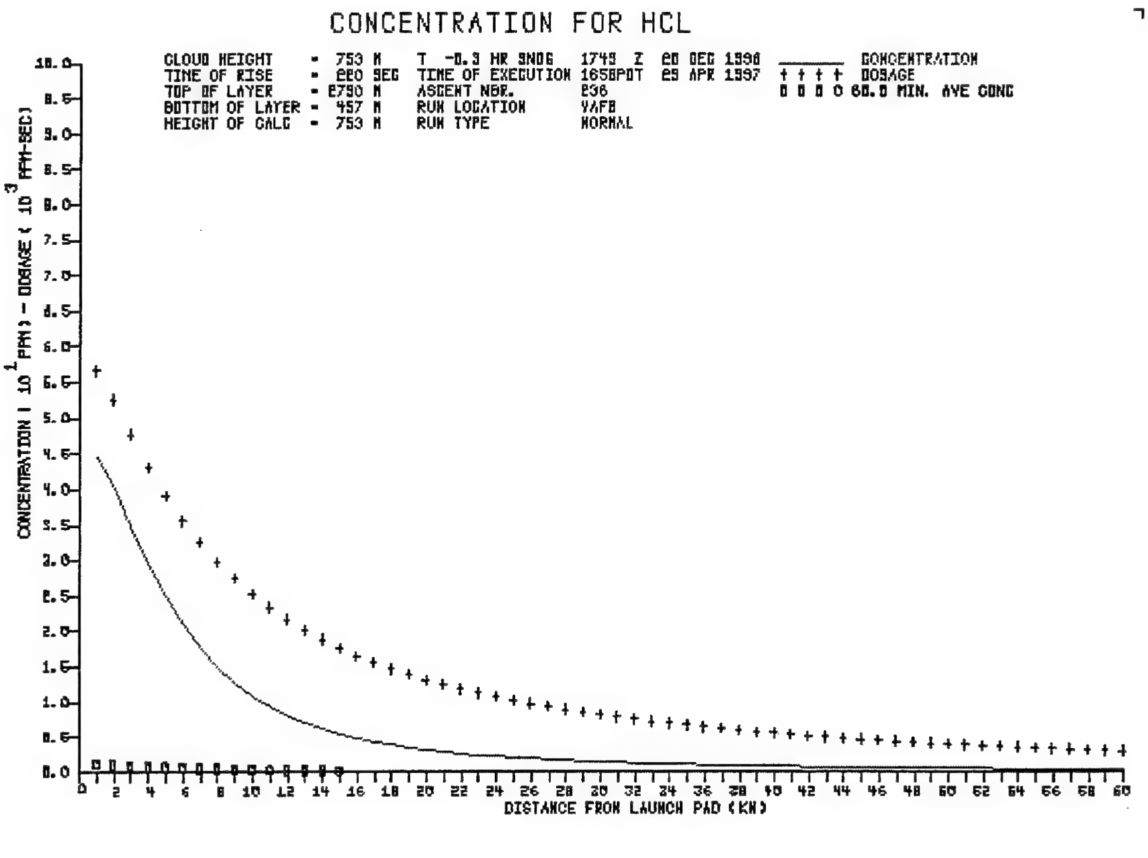



Figure 2. REEDM 7.08 prediction of HCl concentrations at the stabilization height based upon T-0h input.

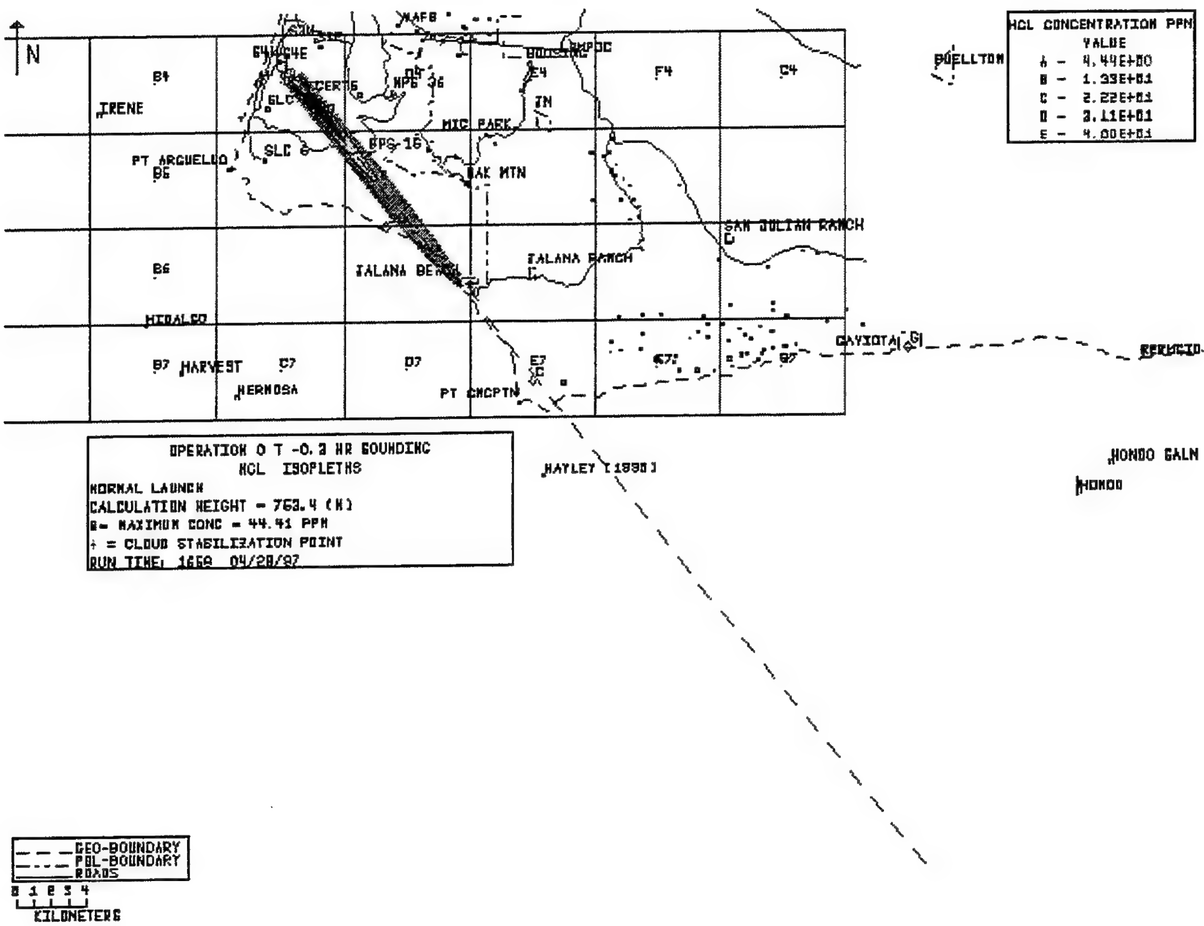



Figure 3. REEDM 7.08 prediction of HCl concentration isopleths at the stabilization height based upon T-0h input.

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1*****************************************************************************
                ROCKET EXHAUST EFFLUENT DIFFUSION MODEL REEDM       PAGE    2
                            VERSION 7.08 AT VAFB
                            1658 PDT 29 APR 1997
                     launch time:  1004 PST 20 DEC 1996
     RAWINSONDE ASCENT NUMBER    236, 1749   Z 20 DEC 1996  T  -0.3 HR
*****************************************************************************

                         ----- PROGRAM OPTIONS -----

  MODEL                                                        CONCENTRATION
  RUN TYPE                                                       OPERATIONAL
  WIND-FIELD TERRAIN EFFECTS MODEL                                      NONE
  LAUNCH VEHICLE                                                    TITAN IV
  LAUNCH TYPE                                                         NORMAL
  LAUNCH COMPLEX NUMBER                                                   4E
  TURBULENCE PARAMETERS ARE DETERMINED FROM               DOPPLER & TOWER DATA
  SURFACE CHEMISTRY MODEL                                absorption coefficient
  SPECIES        SURFACE FACTOR                               HCL        0.000
  CLOUD SHAPE                                                     ELLIPTICAL
  CALCULATION HEIGHT                                           STABILIZATION
  PROPELLANT TEMPERATURE (DEG. C)                                      13.00
  CONCENTRATION AVERAGING TIME (SEC.)                                3600.00
  mixing layer reflection coefficient (RNG- 0 TO 1,no reflection=0)   1.0000
  DIFFUSION COEFFICIENTS                                    LATERAL    1.0000
                                                            VERTICAL   1.0000
  VEHICLE AIR ENTRAINMENT PARAMETER                         GAMMAE     0.6400
  DOWNWIND EXPANSION DISTANCE (METERS)                      LATERAL    100.00
                                                            VERTICAL   100.00

                            ----- DATA FILES -----

                                 INPUT FILES
  RAWINSONDE FILE                                               w6777rin.new
  DATA BASE FILE                                                rdmbase.vaf

                                 OUTPUT FILES
  PRINT FILE                                                    k13t0new.stb
  PLOT FILE                                                     k13t0new.stp
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VERSION 7.08 AT VAFB

1658 PDT 29 APR 1997

launch time: 1004 PST 20 DEC 1996

RAWINSONDE ASCENT NUMBER 236, 1749 Z 20 DEC 1996 T -0.3 HR

*************************************************************************

----- METEOROLOGICAL RAWINSONDE DATA -----

TEST NBR SITE: 1764 OP NO: W6777 ASC NO: 236

RAWINSONDE MSS/WIN

TIME- 1749 Z DATE- 20 DEC 1996

ASCENT NUMBER 236

----- T -0.3 HR SOUNDING -----

| MET. LEV. NO. | ALTITUDE MSL (FT) | ALTITUDE GND (FT) | GND (M) | WIND DIR (DEG) | WIND SPEED (M/S) | WIND SPEED (KTS) | TEMP (DEG C) | AIR PTEMP (DEG C) | DPTEMP (DEG C) | AIR PRESS (MB) | AIR RH (%) | H M | INT-ERP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 328 | 0.0 | 0.0 | 56 | 2.6 | 5.0 | 16.0 | 16.2 | 4.0 | 1008.2 | 44.7 | | |
| 2 | 383 | 54.9 | 16.7 | 70 | 2.1 | 4.0 | 15.9 | 16.2 | 3.6 | 1006.2 | 43.9 | | |
| 3 | 431 | 102.9 | 31.4 | 65 | 2.1 | 4.0 | 15.8 | 16.3 | 3.3 | 1004.5 | 43.1 | | |
| 4 | 465 | 136.9 | 41.7 | 83 | 2.1 | 4.0 | 15.7 | 16.3 | 3.1 | 1003.2 | 42.6 | | ** |
| 5 | 499 | 170.9 | 52.1 | 102 | 2.1 | 4.0 | 15.7 | 16.3 | 2.8 | 1002.0 | 42.1 | | ** |
| 6 | 533 | 204.9 | 62.5 | 120 | 2.1 | 4.0 | 15.6 | 16.3 | 2.6 | 1000.8 | 41.5 | | |
| 7 | 595 | 266.9 | 81.4 | 101 | 1.5 | 3.0 | 15.5 | 16.4 | 2.2 | 998.5 | 40.7 | | ** |
| 8 | 657 | 328.9 | 100.3 | 81 | 1.0 | 1.9 | 15.4 | 16.5 | 1.8 | 996.3 | 39.9 | | |
| 9 | 739 | 410.9 | 125.2 | 62 | 1.1 | 2.1 | 15.4 | 16.7 | 1.5 | 993.3 | 39.0 | | ** |
| 10 | 821 | 492.9 | 150.2 | 42 | 1.2 | 2.3 | 15.3 | 16.8 | 1.1 | 990.4 | 38.2 | | |
| 11 | 903 | 574.9 | 175.2 | 53 | 1.4 | 2.8 | 15.2 | 17.0 | 0.7 | 987.5 | 37.3 | | ** |
| 12 | 985 | 656.9 | 200.2 | 63 | 1.7 | 3.3 | 15.1 | 17.1 | 0.3 | 984.5 | 36.5 | | |
| 13 | 1026 | 697.9 | 212.7 | 47 | 1.5 | 3.0 | 15.0 | 17.2 | 0.1 | 983.1 | 36.1 | | ** |
| 14 | 1067 | 738.9 | 225.2 | 30 | 1.3 | 2.6 | 15.0 | 17.2 | -0.1 | 981.6 | 35.7 | | ** |
| 15 | 1108 | 779.9 | 237.7 | 14 | 1.2 | 2.3 | 15.0 | 17.3 | -0.3 | 980.2 | 35.3 | | ** |
| 16 | 1149 | 820.9 | 250.2 | 358 | 1.0 | 1.9 | 14.9 | 17.4 | -0.5 | 978.7 | 34.9 | | |
| 17 | 1231 | 902.9 | 275.2 | 341 | 1.0 | 1.9 | 14.9 | 17.5 | -0.9 | 975.8 | 34.0 | | ** |
| 18 | 1313 | 984.9 | 300.2 | 325 | 1.0 | 1.9 | 14.8 | 17.7 | -1.3 | 972.9 | 33.2 | | |
| 19 | 1389 | 1060.9 | 323.4 | 309 | 2.2 | 4.3 | 14.7 | 17.8 | -1.6 | 970.3 | 32.5 | | ** |
| 20 | 1465 | 1136.9 | 346.5 | 292 | 3.4 | 6.6 | 14.6 | 17.9 | -2.0 | 967.6 | 31.7 | | |
| 21 | 1600 | 1272.2 | 387.8 | 310 | 3.0 | 5.8 | 14.7 | 18.4 | -3.9 | 962.9 | 27.4 | | ** |
| 22 | 1736 | 1407.6 | 429.0 | 327 | 2.6 | 5.0 | 14.9 | 18.9 | -5.9 | 958.2 | 23.5 | | ** |
| 23 | 1829 | 1500.8 | 457.4 | 339 | 2.3 | 4.4 | 15.0 | 19.2 | -7.2 | 955.0 | 20.0 | * | ** |
| 24 | 1871 | 1542.9 | 470.3 | 345 | 2.2 | 4.2 | 15.0 | 19.4 | -7.8 | 953.5 | 20.0 | | |
| 25 | 2242 | 1914.4 | 583.5 | 341 | 2.8 | 5.4 | 14.8 | 20.2 | -8.1 | 940.9 | 20.0 | | ** |
| 26 | 2614 | 2285.9 | 696.7 | 338 | 3.4 | 6.6 | 14.5 | 21.1 | -8.4 | 928.3 | 19.7 | | |
| 27 | 3167 | 2839.4 | 865.5 | 336 | 3.6 | 7.0 | 13.7 | 22.0 | -10.0 | 909.9 | 18.6 | | ** |
| 28 | 3721 | 3392.9 | 1034.2 | 334 | 3.9 | 7.5 | 12.9 | 22.8 | -11.6 | 891.9 | 16.9 | | |
| 29 | 4258 | 3929.9 | 1197.8 | 329 | 4.0 | 7.8 | 12.8 | 24.3 | -12.3 | 874.6 | 16.6 | | ** |
| 30 | 4795 | 4466.9 | 1361.5 | 324 | 4.2 | 8.1 | 12.6 | 25.8 | -13.0 | 857.8 | 15.4 | | |
| 31 | 5989 | 5660.9 | 1725.4 | 318 | 5.2 | 10.2 | 11.3 | 28.2 | -14.4 | 821.3 | 15.0 | | |
| 32 | 7144 | 6815.9 | 2077.5 | 318 | 6.4 | 12.5 | 9.2 | 29.6 | -15.8 | 787.2 | 15.3 | | |
| 33 | 8537 | 8208.6 | 2502.0 | 315 | 6.6 | 12.9 | 5.5 | 30.2 | -13.4 | 747.6 | 25.0 | | ** |
| 34 | 9482 | 9153.9 | 2790.1 | 313 | 8.1 | 15.7 | 3.4 | 30.9 | -16.9 | 721.7 | 20.8 | | |

* - INDICATES THE CALCULATED TOP OF THE SURFACE MIXING LAYER

** - INDICATES THAT DATA IS LINEARLY INTERPOLATED FROM INPUT METEOROLOGY

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1*************************************************************************
           ROCKET EXHAUST EFFLUENT DIFFUSION MODEL REEDM        PAGE    4
                       VERSION 7.08 AT VAFB
                       1658 PDT 29 APR 1997
                launch time:  1004 PST 20 DEC 1996
     RAWINSONDE ASCENT NUMBER    236, 1749   Z 20 DEC 1996  T  -0.3 HR
**************************************************************************

                ----- METEOROLOGICAL RAWINSONDE DATA -----


 SURFACE AIR DENSITY (GM/M**3)                                        1211.19
 MIXING LAYER HEIGHT   457.43 (M) SPECIFIED BY PRESSURE LEVEL (MB)     954.99
 CLOUD COVER IN TENTHS OF CELESTIAL DOME                                  2.0
 CLOUD CEILING (M)                                                     7620.0

***REEDM  WARNING 09, END OF FILE READ, DATA MAY BE TRUNCATED, FILE =
                w6777rin.new
                 THE ERROR OCCURRED AT RECORD   59.00

***REEDM  ERROR 09, INCOMPLETE DATA - DOPPLER
                 THE ERROR OCCURRED AT RECORD   59.00
                     ----- PLUME RISE DATA -----

EXHAUST RATE OF MATERIAL INTO GRN CLD-    (GRAMS/SEC)           4.14271E+06
TOTAL GROUND CLD MATERIAL-                (GRAMS)               3.89920E+07
HEAT OUTPUT PER GRAM-                     (CALORIES)                 1555.6
VEHICLE RISE HEIGHT DEFINING GROUND CLD-  (M)                         199.9
VEHICLE RISE TIME PARAMETERS-             (TK=(A*Z**B)+C)  A=        0.8677
                                                           B=        0.4500
                                                           C=        0.0000
EXHAUST RATE OF MATERIAL INTO CONTRAIL-   (GRAMS/SEC)           4.14271E+06
CONTRAIL HEAT OUTPUT PER GRAM-            (CALORIES)                 1555.6
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1658 PDT 29 APR 1997
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----- EXHAUST CLOUD -----

| MET. LAYER NO. | TOP OF LAYER (METERS) | CLOUD RISE TIME (SECONDS) | CLOUD RISE RANGE (METERS) | CLOUD RISE BEARING (DEGREES) | STABILIZED CLOUD RANGE (METERS) | STABILIZED CLOUD BEARING (DEGREES) |
|---|---|---|---|---|---|---|
| 1 | 16.7 | 2.2 | 2.6 | 238.9 | 0.0 | 0.0 |
| 2 | 31.4 | 3.3 | 6.1 | 243.5 | 0.0 | 0.0 |
| 3 | 41.7 | 4.1 | 8.0 | 244.5 | 0.0 | 0.0 |
| 4 | 52.1 | 4.8 | 9.5 | 247.5 | 0.0 | 0.0 |
| 5 | 62.5 | 5.6 | 10.9 | 252.3 | 0.0 | 0.0 |
| 6 | 81.4 | 7.2 | 12.7 | 259.4 | 0.0 | 0.0 |
| 7 | 100.3 | 8.8 | 14.9 | 262.9 | 0.0 | 0.0 |
| 8 | 125.2 | 11.2 | 17.0 | 262.7 | 0.0 | 0.0 |
| 9 | 150.2 | 13.8 | 19.5 | 259.8 | 0.0 | 0.0 |
| 10 | 175.2 | 16.7 | 22.3 | 255.0 | 0.0 | 0.0 |
| 11 | 200.2 | 19.8 | 26.4 | 251.5 | 0.0 | 0.0 |
| 12 | 212.7 | 21.5 | 30.2 | 250.1 | 0.0 | 0.0 |
| 13 | 225.2 | 23.2 | 32.6 | 248.3 | 0.0 | 0.0 |
| 14 | 237.7 | 25.0 | 34.4 | 246.0 | 0.0 | 0.0 |
| 15 | 250.2 | 26.8 | 35.8 | 243.3 | 0.0 | 0.0 |
| 16 | 275.2 | 30.7 | 37.0 | 239.2 | 205.5 | 179.2 |
| 17 | 300.2 | 34.8 | 38.0 | 233.4 | 195.7 | 164.1 |
| 18 | 323.4 | 38.8 | 38.2 | 226.5 | 293.1 | 144.2 |
| 19 | 346.5 | 43.1 | 37.7 | 212.8 | 495.9 | 124.7 |
| 20 | 387.8 | 51.2 | 40.4 | 183.6 | 559.5 | 124.6 |
| 21 | 429.0 | 60.2 | 58.7 | 163.2 | 499.2 | 141.2 |
| 22 | 457.4 | 66.8 | 78.1 | 158.7 | 451.2 | 154.0 |
| 23 | 470.3 | 70.0 | 89.5 | 158.5 | 424.1 | 161.1 |
| 24 | 583.5 | 102.8 | 130.8 | 160.1 | 421.3 | 162.1 |
| 25 | 696.7 | 152.1 | 246.1 | 160.6 | 457.1 | 160.2 |
| 26 | 865.5 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |
| 27 | 1034.2 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |
| 28 | 1197.8 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |
| 29 | 1361.5 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |
| 30 | 1725.4 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |
| 31 | 2077.5 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |
| 32 | 2502.0 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |
| 33 | 2790.1 | 220.4 * | 560.6 | 159.2 | 560.6 | 159.2 |

* - INDICATES CLOUD STABILIZATION TIME WAS USED

1*************************************************************************
ROCKET EXHAUST EFFLUENT DIFFUSION MODEL REEDM PAGE 6
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----- EXHAUST CLOUD -----

CHEMICAL SPECIES = HCL

| MET. LAYER NO. | TOP OF LAYER (METERS) | LAYER SOURCE STRENGTH (GRAMS) | CLOUD UPDRAFT VELOCITY (M/S) | CLOUD RADIUS (METERS) | STD. DEVIATION MATERIAL DIST. ALONGWIND (METERS) | CROSSWIND (METERS) |
|---|---|---|---|---|---|---|
| 1 | 16.7 | 0.00000E+00 | 12.2 | 0.0 | 0.0 | 0.0 |
| 2 | 31.4 | 0.00000E+00 | 13.4 | 0.0 | 0.0 | 0.0 |
| 3 | 41.7 | 0.00000E+00 | 13.4 | 0.0 | 0.0 | 0.0 |
| 4 | 52.1 | 0.00000E+00 | 13.1 | 0.0 | 0.0 | 0.0 |
| 5 | 62.5 | 0.00000E+00 | 12.7 | 0.0 | 0.0 | 0.0 |
| 6 | 81.4 | 0.00000E+00 | 11.9 | 0.0 | 0.0 | 0.0 |
| 7 | 100.3 | 0.00000E+00 | 11.0 | 0.0 | 0.0 | 0.0 |
| 8 | 125.2 | 0.00000E+00 | 10.0 | 0.0 | 0.0 | 0.0 |
| 9 | 150.2 | 0.00000E+00 | 9.1 | 0.0 | 0.0 | 0.0 |
| 10 | 175.2 | 0.00000E+00 | 8.4 | 0.0 | 0.0 | 0.0 |
| 11 | 200.2 | 0.00000E+00 | 7.7 | 0.0 | 0.0 | 0.0 |
| 12 | 212.7 | 0.00000E+00 | 7.4 | 0.0 | 0.0 | 0.0 |
| 13 | 225.2 | 0.00000E+00 | 7.1 | 0.0 | 0.0 | 0.0 |
| 14 | 237.7 | 0.00000E+00 | 6.9 | 0.0 | 0.0 | 0.0 |
| 15 | 250.2 | 0.00000E+00 | 6.7 | 0.0 | 0.0 | 0.0 |
| 16 | 275.2 | 5.06591E+02 | 6.3 | 108.4 | 50.5 | 50.5 |
| 17 | 300.2 | 3.51766E+04 | 5.9 | 140.8 | 65.6 | 65.6 |
| 18 | 323.4 | 8.02433E+04 | 5.6 | 220.7 | 102.8 | 102.8 |
| 19 | 346.5 | 1.23674E+05 | 5.3 | 273.9 | 127.6 | 127.6 |
| 20 | 387.8 | 3.20451E+05 | 4.8 | 330.6 | 154.0 | 154.0 |
| 21 | 429.0 | 4.37537E+05 | 4.4 | 386.2 | 179.9 | 179.9 |
| 22 | 457.4 | 3.62455E+05 | 4.1 | 423.4 | 197.3 | 197.3 |
| 23 | 470.3 | 1.78956E+05 | 4.0 | 442.3 | 206.1 | 206.1 |
| 24 | 583.5 | 1.91276E+06 | 2.9 | 488.5 | 227.6 | 227.6 |
| 25 | 696.7 | 2.32271E+06 | 1.7 | 538.0 | 250.7 | 250.7 |
| 26 | 865.5 * | 4.53337E+06 | 0.0 | 552.6 | 257.5 | 257.5 |
| 27 | 1034.2 * | 4.27522E+06 | 0.0 | 505.4 | 235.5 | 235.5 |
| 28 | 1197.8 * | 2.61608E+06 | 0.0 | 364.2 | 169.7 | 169.7 |
| 29 | 1361.5 * | 1.08465E+06 | 0.0 | 213.0 | 99.3 | 99.3 |
| 30 | 1725.4 * | 2.05652E+06 | 0.0 | 199.9 | 93.2 | 93.2 |
| 31 | 2077.5 * | 1.77236E+06 | 0.0 | 199.9 | 93.2 | 93.2 |
| 32 | 2502.0 * | 1.92945E+06 | 0.0 | 199.9 | 93.2 | 93.2 |
| 33 | 2790.1 * | 1.20857E+06 | 0.0 | 199.9 | 93.2 | 93.2 |

* - INDICATES CLOUD STABILIZATION TIME WAS USED

----- CLOUD STABILIZATION -----

| | | | |
|---|---|---|---|
| CALCULATION HEIGHT | (METERS) | | 753.39 |
| STABILIZATION HEIGHT | (METERS) | | 753.39 |
| STABILIZATION TIME | (SECS) | | 220.45 |
| FIRST MIXING LAYER HEIGHT- | (METERS) | TOP = | 457.43 |
| | | BASE= | 0.00 |
| SECOND SELECTED LAYER HEIGHT- | (METERS) | TOP = | 2790.11 |
| | | BASE= | 457.43 |
| SIGMAR(AZ) AT THE SURFACE | (DEGREES) | | 8.0417 |
| SIGMER(EL) AT THE SURFACE | (DEGREES) | | 1.0000 |

| MET. LAYER NO. | WIND SPEED (M/SEC) | WIND SPEED SHEAR (M/SEC) | WIND DIRECTION (DEG) | WIND DIRECTION SHEAR (DEG) | SIGMA OF AZI ANG (DEG) | SIGMA OF ELE ANG (DEG) |
|---|---|---|---|---|---|---|
| 1 | 2.57 | -0.51 | 63.00 | 14.00 | 5.5265 | 1.0000 |
| 2 | 2.06 | 0.00 | 67.50 | -5.00 | 2.5731 | 1.0000 |
| 3 | 2.06 | 0.00 | 74.17 | 18.33 | 2.2576 | 1.0000 |
| 4 | 2.06 | 0.00 | 92.50 | 18.33 | 2.5031 | 1.0000 |
| 5 | 2.06 | 0.00 | 110.83 | 18.33 | 2.7554 | 1.0000 |
| 6 | 1.79 | -0.53 | 110.25 | -19.50 | 3.5639 | 1.0000 |
| 7 | 1.26 | -0.53 | 90.75 | -19.50 | 4.6340 | 1.0727 |
| 8 | 1.05 | 0.09 | 71.25 | -19.50 | 9.2805 | 7.3407 |
| 9 | 1.14 | 0.09 | 51.75 | -19.50 | 18.6678 | 18.6678 |
| 10 | 1.31 | 0.26 | 47.25 | 10.50 | 18.7416 | 18.7416 |
| 11 | 1.57 | 0.26 | 57.75 | 10.50 | 10.1945 | 10.1945 |
| 12 | 1.61 | -0.17 | 54.83 | -16.35 | 7.5055 | 7.5055 |
| 13 | 1.44 | -0.17 | 38.48 | -16.35 | 9.3127 | 9.3127 |
| 14 | 1.26 | -0.17 | 22.13 | -16.35 | 11.6260 | 11.6260 |
| 15 | 1.09 | -0.17 | 5.78 | -16.35 | 14.6940 | 14.6940 |
| 16 | 1.00 | 0.00 | 349.42 | -16.35 | 17.7240 | 17.7240 |
| 17 | 1.00 | 0.00 | 333.08 | -16.35 | 20.2169 | 20.2169 |
| 18 | 1.60 | 1.20 | 316.73 | -16.35 | 14.4995 | 14.4995 |
| 19 | 2.80 | 1.20 | 300.38 | -16.35 | 5.5212 | 5.5212 |
| 20 | 3.19 | -0.41 | 300.92 | 17.43 | 3.2688 | 3.2688 |
| 21 | 2.78 | -0.41 | 318.35 | 17.43 | 2.4448 | 2.4448 |
| 22 | 2.43 | -0.28 | 333.07 | 12.00 | 1.4185 | 1.4185 |
| 23 | 2.22 | -0.13 | 341.79 | 5.43 | 1.0000 | 1.0000 |
| 24 | 2.47 | 0.62 | 342.95 | -3.10 | 1.0000 | 1.0000 |
| 25 | 3.09 | 0.62 | 339.85 | -3.10 | 1.0000 | 1.0000 |
| 26 | 3.51 | 0.23 | 337.22 | -2.15 | 1.0000 | 1.0000 |
| 27 | 3.74 | 0.23 | 335.08 | -2.15 | 1.0000 | 1.0000 |
| 28 | 3.94 | 0.15 | 331.55 | -4.90 | 1.0000 | 1.0000 |
| 29 | 4.09 | 0.15 | 326.65 | -4.90 | 1.0000 | 1.0000 |
| 30 | 4.71 | 1.08 | 321.30 | -5.80 | 1.0000 | 1.0000 |

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----- CALCULATED METEOROLOGICAL LAYER PARAMETERS -----

| MET. LAYER NO. | WIND SPEED (M/SEC) | WIND SPEED SHEAR (M/SEC) | WIND DIRECTION (DEG) | WIND DIRECTION SHEAR (DEG) | SIGMA OF AZI ANG (DEG) | SIGMA OF ELE ANG (DEG) |
|---|---|---|---|---|---|---|
| 31 | 5.84 | 1.18 | 318.25 | -0.30 | 1.0000 | 1.0000 |
| 32 | 6.53 | 0.21 | 316.60 | -3.00 | 1.0000 | 1.0000 |
| 33 | 7.36 | 1.44 | 314.10 | -2.00 | 1.0000 | 1.0000 |

ALTITUDE RANGE USED IN COMPUTING TRANSITION LAYER AVERAGES
IS 250.2 TO 2790.1 METERS.

TRANSITION LAYER NUMBER- 1

| VALUE | HEIGHT (METERS) | TEMP. (DEG K) | WIND SPEED (M/SEC) | WIND SPEED SHEAR (M/SEC) | WIND DIR. (DEG) | WIND DIR. SHEAR (DEG) | SIGMA AZI. (DEG) | SIGMA AT ELE. (DEG) |
|---|---|---|---|---|---|---|---|---|
| TOP- | 457.43 | 292.35 | 2.29 | | 339.07 | | 1.0000 | 1.0000 |
| LAYER- | | | 2.18 | 0.86 | 315.35 | 17.01 | 8.1461 | 8.1461 |
| BOTTOM- | 0.00 | 289.35 | 2.57 | | 56.00 | | 8.0417 | 1.0000 |

TRANSITION LAYER NUMBER- 2

| VALUE | HEIGHT (METERS) | TEMP. (DEG K) | WIND SPEED (M/SEC) | WIND SPEED SHEAR (M/SEC) | WIND DIR. (DEG) | WIND DIR. SHEAR (DEG) | SIGMA AZI. (DEG) | SIGMA AT ELE. (DEG) |
|---|---|---|---|---|---|---|---|---|
| TOP- | 2790.11 | 304.04 | 8.08 | | 313.10 | | 1.0000 | 1.0000 |
| LAYER- | | | 5.03 | 1.56 | 321.85 | 7.78 | 1.0000 | 1.0000 |
| BOTTOM- | 457.43 | 292.35 | 2.29 | | 339.07 | | 1.0000 | 1.0000 |

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RAWINSONDE ASCENT NUMBER 236, 1749 Z 20 DEC 1996 T -0.3 HR
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----- MAXIMUM CENTERLINE CALCULATIONS -----

** DECAY COEFFICIENT (1/SEC) = 0.00000E+00 **

CONCENTRATION OF HCL AT A HEIGHT OF 753.4 METERS
DOWNWIND FROM A TITAN IV NORMAL LAUNCH
CALCULATIONS APPLY TO THE LAYER BETWEEN 457.4 AND 2790.1 METERS

| RANGE FROM PAD (METERS) | BEARING FROM PAD (DEGREES) | PEAK CONCEN-TRATION (PPM) | CLOUD ARRIVAL TIME (MIN) | CLOUD DEPARTURE TIME (MIN) |
|---|---|---|---|---|
| 1000.0026 | 151.4884 | 44.4075 | 2.5712 | 7.0088 |
| 2000.0001 | 146.6513 | 40.1675 | 5.3114 | 10.3935 |
| 3000.0000 | 145.0477 | 34.7905 | 8.0913 | 13.8109 |
| 4000.0000 | 144.2469 | 29.4880 | 11.2401 | 17.2655 |
| 5000.0000 | 143.7667 | 24.8471 | 14.3543 | 20.7520 |
| 6000.0000 | 143.4466 | 20.9029 | 17.4434 | 24.2645 |
| 7000.0000 | 143.2180 | 17.6068 | 20.5143 | 27.7973 |
| 8000.0000 | 143.0465 | 14.8802 | 23.5718 | 31.3461 |
| 9000.0000 | 142.9132 | 12.6358 | 26.6194 | 34.9072 |
| 10000.0000 | 142.8065 | 10.7906 | 29.6594 | 38.4782 |
| 11000.0000 | 142.7193 | 9.2719 | 32.6937 | 42.0569 |
| 12000.0000 | 142.6465 | 8.0183 | 35.7234 | 45.6418 |
| 13000.0000 | 142.5850 | 6.9790 | 38.7495 | 49.2318 |
| 14000.0000 | 142.5323 | 6.1132 | 41.7727 | 52.8258 |
| 15000.9355 | 142.4865 | 5.3869 | 44.7963 | 56.4267 |
| 16000.8770 | 142.4465 | 4.7751 | 47.8149 | 60.0267 |
| 17000.8262 | 142.4113 | 4.2557 | 50.8320 | 63.6292 |
| 18000.7793 | 142.3799 | 3.8119 | 53.8477 | 67.2337 |
| 19000.7383 | 142.3518 | 3.4302 | 56.8622 | 70.8400 |
| 20000.7012 | 142.3266 | 3.0998 | 59.8757 | 74.4477 |
| 21000.6680 | 142.3037 | 2.8121 | 62.8884 | 78.0568 |
| 22000.6367 | 142.2829 | 2.5602 | 65.9004 | 81.6669 |
| 23000.6094 | 142.2640 | 2.3384 | 68.9117 | 85.2781 |
| 24000.5840 | 142.2466 | 2.1422 | 71.9224 | 88.8902 |
| 25000.5605 | 142.2306 | 1.9680 | 74.9326 | 92.5030 |
| 26000.5391 | 142.2158 | 1.8125 | 77.9424 | 96.1164 |
| 27000.5195 | 142.2022 | 1.6733 | 80.9518 | 99.7305 |
| 28000.5020 | 142.1895 | 1.5481 | 83.9609 | 103.3452 |
| 29000.4844 | 142.1776 | 1.4354 | 86.9696 | 106.9603 |
| 30000.4668 | 142.1666 | 1.3334 | 89.9780 | 110.5759 |
| 31000.4531 | 142.1563 | 1.2410 | 92.9862 | 114.1919 |
| 32000.4375 | 142.1466 | 1.1569 | 95.9941 | 117.8082 |
| 33000.4258 | 142.1375 | 1.0804 | 99.0018 | 121.4249 |
| 34000.4141 | 142.1290 | 1.0105 | 102.0094 | 125.0419 |
| 35000.4023 | 142.1209 | 0.9466 | 105.0167 | 128.6592 |

----- MAXIMUM CENTERLINE CALCULATIONS -----

** DECAY COEFFICIENT (1/SEC) = 0.00000E+00 **

CONCENTRATION OF HCL AT A HEIGHT OF 753.4 METERS
DOWNWIND FROM A TITAN IV NORMAL LAUNCH
CALCULATIONS APPLY TO THE LAYER BETWEEN 457.4 AND 2790.1 METERS

| RANGE FROM PAD (METERS) | BEARING FROM PAD (DEGREES) | PEAK CONCEN-TRATION (PPM) | CLOUD ARRIVAL TIME (MIN) | CLOUD DEPARTURE TIME (MIN) |
|---|---|---|---|---|
| 36000.3906 | 142.1133 | 0.8879 | 108.0239 | 132.2767 |
| 37000.3789 | 142.1061 | 0.8341 | 111.0309 | 135.8944 |
| 38000.3711 | 142.0993 | 0.7845 | 114.0378 | 139.5124 |
| 39000.3594 | 142.0928 | 0.7389 | 117.0446 | 143.1305 |
| 40000.3516 | 142.0866 | 0.6967 | 120.0513 | 146.7489 |
| 41000.3438 | 142.0808 | 0.6577 | 123.0578 | 150.3674 |
| 42000.3359 | 142.0752 | 0.6216 | 126.0642 | 153.9861 |
| 43000.3281 | 142.0699 | 0.5881 | 129.0706 | 157.6049 |
| 44000.3203 | 142.0648 | 0.5570 | 132.0768 | 161.2239 |
| 45000.3125 | 142.0600 | 0.5281 | 135.0830 | 164.8430 |
| 46000.3047 | 142.0553 | 0.5012 | 138.0891 | 168.4622 |
| 47000.2969 | 142.0509 | 0.4761 | 141.0951 | 172.0816 |
| 48000.2930 | 142.0466 | 0.4527 | 144.1011 | 175.7010 |
| 49000.2852 | 142.0426 | 0.4308 | 147.1070 | 179.3205 |
| 50000.2813 | 142.0386 | 0.4103 | 150.1128 | 182.9401 |
| 51000.2734 | 142.0349 | 0.3911 | 153.1186 | 186.5599 |
| 52000.2695 | 142.0313 | 0.3732 | 156.1243 | 190.1797 |
| 53000.2656 | 142.0278 | 0.3563 | 159.1299 | 193.7996 |
| 54000.2578 | 142.0244 | 0.3405 | 162.1356 | 197.4195 |
| 55000.2539 | 142.0212 | 0.3256 | 165.1411 | 201.0396 |
| 56000.2500 | 142.0181 | 0.3116 | 168.1467 | 204.6597 |
| 57000.2461 | 142.0151 | 0.2984 | 171.1522 | 208.2798 |
| 58000.2422 | 142.0122 | 0.2859 | 174.1576 | 211.9000 |
| 59000.2383 | 142.0094 | 0.2742 | 177.1630 | 215.5203 |
| 60000.2344 | 142.0067 | 0.2631 | 180.1685 | 219.1406 |

| | RANGE | BEARING |
|---|---|---|
| 44.408 IS THE MAXIMUM PEAK CONCENTRATION | 1000.0 | 151.5 |

----- MAXIMUM CENTERLINE CALCULATIONS -----

** DECAY COEFFICIENT (1/SEC) = 0.00000E+00 **

CONCENTRATION OF HCL AT A HEIGHT OF 753.4 METERS
DOWNWIND FROM A TITAN IV NORMAL LAUNCH
CALCULATIONS APPLY TO THE LAYER BETWEEN 457.4 AND 2790.1 METERS

| RANGE FROM PAD (METERS) | BEARING FROM PAD (DEGREES) | 60.0 MIN. MEAN CONCEN-TRATION (PPM) | CLOUD ARRIVAL TIME (MIN) | CLOUD DEPARTURE TIME (MIN) |
|---|---|---|---|---|
| 1000.0026 | 151.4884 | 1.5873 | 2.5712 | 7.0088 |
| 2000.0001 | 146.6513 | 1.4737 | 5.3114 | 10.3935 |
| 3000.0000 | 145.0477 | 1.3399 | 8.0913 | 13.8109 |
| 4000.0000 | 144.2469 | 1.2114 | 11.2401 | 17.2655 |
| 5000.0000 | 143.7667 | 1.1001 | 14.3543 | 20.7520 |
| 6000.0000 | 143.4466 | 1.0032 | 17.4434 | 24.2645 |
| 7000.0000 | 143.2180 | 0.9179 | 20.5143 | 27.7973 |
| 8000.0000 | 143.0465 | 0.8424 | 23.5718 | 31.3461 |
| 9000.0000 | 142.9132 | 0.7753 | 26.6194 | 34.9072 |
| 10000.0000 | 142.8065 | 0.7155 | 29.6594 | 38.4782 |
| 11000.0000 | 142.7193 | 0.6623 | 32.6937 | 42.0569 |
| 12000.0000 | 142.6465 | 0.6150 | 35.7234 | 45.6418 |
| 13000.0000 | 142.5850 | 0.5728 | 38.7495 | 49.2318 |
| 14000.0000 | 142.5323 | 0.5351 | 41.7727 | 52.8258 |
| 15000.9355 | 142.4865 | 0.5014 | 44.7963 | 56.4267 |
| 16000.8770 | 142.4465 | 0.4711 | 47.8149 | 60.0267 |
| 17000.8262 | 142.4113 | 0.4439 | 50.8320 | 63.6292 |
| 18000.7793 | 142.3799 | 0.4193 | 53.8477 | 67.2337 |
| 19000.7383 | 142.3518 | 0.3969 | 56.8622 | 70.8400 |
| 20000.7012 | 142.3266 | 0.3765 | 59.8757 | 74.4477 |
| 21000.6680 | 142.3037 | 0.3577 | 62.8884 | 78.0568 |
| 22000.6367 | 142.2829 | 0.3405 | 65.9004 | 81.6669 |
| 23000.6094 | 142.2640 | 0.3246 | 68.9117 | 85.2781 |
| 24000.5840 | 142.2466 | 0.3098 | 71.9224 | 88.8902 |
| 25000.5605 | 142.2306 | 0.2961 | 74.9326 | 92.5030 |
| 26000.5391 | 142.2158 | 0.2833 | 77.9424 | 96.1164 |
| 27000.5195 | 142.2022 | 0.2714 | 80.9518 | 99.7305 |
| 28000.5020 | 142.1895 | 0.2602 | 83.9609 | 103.3452 |
| 29000.4844 | 142.1776 | 0.2496 | 86.9696 | 106.9603 |
| 30000.4668 | 142.1666 | 0.2398 | 89.9780 | 110.5759 |
| 31000.4531 | 142.1563 | 0.2304 | 92.9862 | 114.1919 |
| 32000.4375 | 142.1466 | 0.2217 | 95.9941 | 117.8082 |
| 33000.4258 | 142.1375 | 0.2134 | 99.0018 | 121.4249 |
| 34000.4141 | 142.1290 | 0.2056 | 102.0094 | 125.0419 |

VERSION 7.08 AT VAFB
1658 PDT 29 APR 1997
launch time: 1004 PST 20 DEC 1996
RAWINSONDE ASCENT NUMBER 236, 1749 Z 20 DEC 1996 T -0.3 HR
***************************************************************************

----- MAXIMUM CENTERLINE CALCULATIONS -----

** DECAY COEFFICIENT (1/SEC) = 0.00000E+00 **

CONCENTRATION OF HCL AT A HEIGHT OF 753.4 METERS
DOWNWIND FROM A TITAN IV NORMAL LAUNCH
CALCULATIONS APPLY TO THE LAYER BETWEEN 457.4 AND 2790.1 METERS

| RANGE FROM PAD (METERS) | BEARING FROM PAD (DEGREES) | 60.0 MIN. MEAN CONCEN-TRATION (PPM) | CLOUD ARRIVAL TIME (MIN) | CLOUD DEPARTURE TIME (MIN) |
|---|---|---|---|---|
| 35000.4023 | 142.1209 | 0.1981 | 105.0167 | 128.6592 |
| 36000.3906 | 142.1133 | 0.1911 | 108.0239 | 132.2767 |
| 37000.3789 | 142.1061 | 0.1845 | 111.0309 | 135.8944 |
| 38000.3711 | 142.0993 | 0.1782 | 114.0378 | 139.5124 |
| 39000.3594 | 142.0928 | 0.1722 | 117.0446 | 143.1305 |
| 40000.3516 | 142.0866 | 0.1665 | 120.0513 | 146.7489 |
| 41000.3438 | 142.0808 | 0.1611 | 123.0578 | 150.3674 |
| 42000.3359 | 142.0752 | 0.1559 | 126.0642 | 153.9861 |
| 43000.3281 | 142.0699 | 0.1510 | 129.0706 | 157.6049 |
| 44000.3203 | 142.0648 | 0.1464 | 132.0768 | 161.2239 |
| 45000.3125 | 142.0600 | 0.1419 | 135.0830 | 164.8430 |
| 46000.3047 | 142.0553 | 0.1376 | 138.0891 | 168.4622 |
| 47000.2969 | 142.0509 | 0.1336 | 141.0951 | 172.0816 |
| 48000.2930 | 142.0466 | 0.1297 | 144.1011 | 175.7010 |
| 49000.2852 | 142.0426 | 0.1260 | 147.1070 | 179.3205 |
| 50000.2813 | 142.0386 | 0.1225 | 150.1128 | 182.9401 |
| 51000.2734 | 142.0349 | 0.1191 | 153.1186 | 186.5599 |
| 52000.2695 | 142.0313 | 0.1158 | 156.1243 | 190.1797 |
| 53000.2656 | 142.0278 | 0.1127 | 159.1299 | 193.7996 |
| 54000.2578 | 142.0244 | 0.1097 | 162.1356 | 197.4195 |
| 55000.2539 | 142.0212 | 0.1069 | 165.1411 | 201.0396 |
| 56000.2500 | 142.0181 | 0.1041 | 168.1467 | 204.6597 |
| 57000.2461 | 142.0151 | 0.1015 | 171.1522 | 208.2798 |
| 58000.2422 | 142.0122 | 0.0990 | 174.1576 | 211.9000 |
| 59000.2383 | 142.0094 | 0.0965 | 177.1630 | 215.5203 |
| 60000.2344 | 142.0067 | 0.0942 | 180.1685 | 219.1406 |

| | RANGE | BEARING |
|---|---|---|
| 1.587 IS THE MAXIMUM 60.0 MIN. MEAN CONCENTRATION | 1000.0 | 151.5 |

*** REEDM HAS TERMINATED

## Appendix B – Meteorological Input for #K13 Mission (T-0h Revised)

"W6777rin.new"

$ 12/20/96 18:25:57

1820Z 12 20 96 10

| TWR | LVL | HMSL | SPD | DIR | TEMP | RH | TD | SOSD | SOSM | PRESS | SIG-A | SIG-E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 300 | 1 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 10.1 | 1.0 |
| 300 | 54 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 3.7 | 1.0 |
| 300 | 102 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 2.6 | 1.0 |
| 300 | 204 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 3.5 | 1.0 |
| 300 | 275 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 5.4 | 1.0 |
| 300 | 328 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 6.1 | 1.0 |
| 300 | 492 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 4.5 | 23.9 |
| 300 | 656 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 3.1 | 6.7 |
| 300 | 984 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 6.5 | 21.5 |
| 300 | 1136 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.6 | 3.5 |
| 300 | 1542 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 2285 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 3392 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 4466 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 5660 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 6815 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 8904 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 9153 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |
| 300 | 10314 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 999.0 | 1.0 | 1.0 |

$ 12/20/96 18:26:02

UNINTERPOLATED DATA

TEST NBR SITE: 1764 OP NO: W6777 ASC NO: 236

1764

BLDG 1764, VANDENBERG AFB, CALIF.

RAWINSONDE MSS/WIN 4.5 1.7 20

1749Z 20 DEC 1996 954.99 2 7620

ASCENT NBR 236

| ALT | DIR | SPD | TEMP | DEWPT | PRESS | RH | ABH | DENSITY | IR | SOS | S | I |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 329.0 | 56.0 | 5.0 | 16.0 | 4.0 | 1008.20 | 44.7 | 0.0 | 1225.70 | 0.0 | 0.0 | 1 | 9 |
| 383.0 | 70.0 | 4.0 | 15.9 | 3.6 | 1006.23 | 43.9 | 0.0 | 1223.50 | 0.0 | 0.0 | 1 | 0 |
| 431.0 | 65.0 | 4.0 | 15.8 | 3.3 | 1004.47 | 43.1 | 0.0 | 1221.56 | 0.0 | 0.0 | 1 | 0 |
| 533.0 | 120.0 | 4.0 | 15.6 | 2.6 | 1000.76 | 41.5 | 0.0 | 1217.43 | 0.0 | 0.0 | 1 | 0 |
| 657.0 | 66.0 | 1.7 | 15.4 | 1.8 | 996.27 | 39.9 | 0.0 | 1211.72 | 0.0 | 0.0 | 2 | 0 |
| 821.0 | 42.0 | 2.3 | 15.3 | 1.1 | 990.38 | 38.2 | 0.0 | 1202.94 | 0.0 | 0.0 | 2 | 0 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 985.0 | 63.0 | 3.3 | 15.1 | 0.3 | 984.53 | 36.5 | 0.0 | 1194.22 | 0.0 | 0.0 | 2 | 0 |
| 1149.0 | 71.0 | 0.4 | 14.9 | -.5 | 978.71 | 34.9 | 0.0 | 1185.56 | 0.0 | 0.0 | 2 | 0 |
| 1313.0 | 2.0 | 1.6 | 14.8 | -1.3 | 972.93 | 33.2 | 0.0 | 1176.97 | 0.0 | 0.0 | 2 | 0 |
| 1465.0 | 292.2 | 6.6 | 14.6 | -2.0 | 967.60 | 31.7 | 0.0 | 1169.06 | 0.0 | 0.0 | 2 | 9 |
| 1871.0 | 344.5 | 4.2 | 15.0 | -7.8 | 953.54 | 20.0 | 0.0 | 1151.29 | 0.0 | 0.0 | 4 | 9 |
| 2614.0 | 338.3 | 6.6 | 14.5 | -8.4 | 928.34 | 19.7 | 0.0 | 1122.84 | 0.0 | 0.0 | 4 | 0 |
| 3721.0 | 334.0 | 7.5 | 12.9 | -11.6 | 891.87 | 16.9 | 0.0 | 1085.05 | 0.0 | 0.0 | 4 | 9 |
| 4795.0 | 324.2 | 8.1 | 12.6 | -13.0 | 857.76 | 15.4 | 0.0 | 1044.72 | 0.0 | 0.0 | 4 | 9 |
| 5989.0 | 318.4 | 10.2 | 11.3 | -14.4 | 821.25 | 15.0 | 0.0 | 1004.89 | 0.0 | 0.0 | 4 | 9 |
| 7144.0 | 318.1 | 12.5 | 9.2 | -15.8 | 787.22 | 15.3 | 0.0 | 970.49 | 0.0 | 0.0 | 4 | 9 |
| 9233.0 | 313.6 | 13.1 | 3.7 | -12.2 | 728.51 | 30.0 | 0.0 | 915.60 | 0.0 | 0.0 | 4 | 9 |
| 9482.0 | 313.1 | 15.7 | 3.4 | -16.9 | 721.72 | 20.8 | 0.0 | 908.41 | 0.0 | 0.0 | 4 | 9 |
| 10643.0 | 315.3 | 15.7 | 1.1 | -20.1 | 690.83 | 18.7 | 0.0 | 876.96 | 0.0 | 0.0 | 4 | 0 |

EOF

EOT